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The UNIVERSITY of WISCONSIN

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401 930

A SURVEY OF DATA ON MICROSCOPIC EXTRATERRESTRIAL PARTICLES

APR 22 1963

by

Richard A. Schmidt

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RESEARCH REPORT SERIES 63-2 - JANUARY, 1963

11 Research Report Series
Number 63-2
9 January 1963

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The University of Wisconsin
Geophysical and Polar Research Center
6021 South Highland Road
Madison 5, Wisconsin

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illus. tables, refs.

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PREFACE

The problems of conducting a literature survey are many and varied. A major consideration is, of course, assembling pertinent books, reports, articles, and research notes dealing with the subject. The writer was ably assisted in this work by Mrs. Elizabeth Boardman, Librarian of the Geophysical and Polar Research Center at the University of Wisconsin. Her untiring efforts and active interest in this project were of great significance in the completion of this survey.

Many thanks are due to the entire office staff at the Geophysical and Polar Research Center for deciphering my handwriting, correcting my spelling, and typing several rough drafts and the final copy. Without their cheerful assistance, patience, and skill the report could not have been completed so swiftly.

A rough draft of this paper was reviewed by many investigators working on the same general topic. Their many comments, suggestions, criticisms, and warm encouragements were of great value in preparing the final draft. It is a privilege to list them here. Of course, this acknowledgment does not commit these workers to the contents of the survey or to conclusions resulting from it; the writer accepts full responsibility for the final copy.

Reviewers of literature survey:

Dr. John C. Behrendt	University of Wisconsin
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Mr. William Strange	University of Wisconsin
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Dr. Frances W. Wright	Smithsonian Astrophysical Observatory

Finally, it is an honor to acknowledge the guidance, encouragement, and constructive suggestions of Professor George P. Woollard. Truly, this paper and the larger investigation which it heralds were made possible by his interest and support.

This work was part of a project supported by a grant from the National Science Foundation.

PART 1

REVIEW OF PREVIOUS WORK

1. 1. Introduction

Microscopic extraterrestrial particles are the least understood of all materials that reach the Earth from outer space. Indeed, for much of the time since their discovery about a century ago they have been regarded as geological curiosities. Although they were usually mentioned by authors of geological textbooks in discussions of oceanic sedimentation, little was known about the nature of the particles, their origin, or how they came to be deposited on the earth's surface. In spite of the active interest which curiosities commonly inspire among scientists, the small size of the particles and the great difficulty in obtaining samples uncontaminated with terrestrial dusts conspired to thwart many early efforts to unlock their mysteries; yet they occupy a position of critical importance to better understanding of the space environment of our planet.

Space research has provided the impetus for renewed efforts to determine the composition, characteristics, occurrence, and origin of microscopic extraterrestrial particles. These data are of crucial importance to the comprehensive planning of space researches, and especially to the construction of successful, manned, space vehicles. Sophisticated instruments provided through technological advances have simplified the problems of obtaining quantitative data for these microscopic objects. Modern efforts to study the particles are often coordinated and complementary, unlike those conducted in the past. However, to properly evaluate the present research, knowledge of previous studies is essential.

A survey of data on microscopic extraterrestrial ~~particles~~ ~~these~~ particles was undertaken in order to provide an up-to-date compilation of existing knowledge on the subject as a reference for new research being conducted at the Geophysical and Polar Research Center of the University of Wisconsin. The objective of the survey was to bring together as much available data as possible. Principal attention was devoted to the following information about these particles: description, size, physical properties, chemical composition, occurrence, location of samples, annual deposit, and theories of origin.

Many sources of information were employed in this effort; all are listed in alphabetical order in the bibliography. A few works, however, were relied upon more extensively and deserve special mention. The studies of Buddhue from 1940 to 1948 have produced a classic paper on "meteortic dust", published in 1950. This research, an important contribution in its own right, served to arouse new interest in the study of such particles which had been virtually neglected since the time of Murray (1883). Shortly after Buddhue's monograph was published several more reports of

studies of such particles appeared. Another valuable source of articles on "cosmic dust" and interplanetary dust was the annotated bibliography of Hoffleit (1952) and that of Hodge, Wright, and Hoffleit (1961). Still other papers were located through bibliographies compiled by Magnolia (1962) and Salisbury and Salisbury (1961). The remainder of the data summarized here was taken from works listed in the reference lists of the several authors and from the current literature.

Many investigators have studied the occurrence and characteristics of microscopic extraterrestrial particles. A chronological review of work completed prior to 1950 was given by Buddhue in his monograph of that year. Available works completed since then were briefly summarized, in the same manner, in Appendix III at the end of the paper.

1. 2. Definitions

The material treated in this survey has been known by many names, among which are "cosmic dust", "cosmic spherules", "caudaites", "meteoritic dust", "meteoric dust", "micrometeorites", "nanometeorites", "interplanetary dust", "interstellar dust", "primordial dust", "zodiacal dust", "galactic dust", "cometary debris", "planetary debris", and "asteroidal fragments". It is clear that this diversity of terms, often used by different workers to describe the same matter, can be confusing. In an attempt to reduce such confusion, definitions of each are presented below. The first four sub-sections describe materials collected at the surface of the earth. In the strictest sense, these classes of particles are meteorites because of their occurrence. However, the particles have been identified by different terms to provide insight into their origin, and this practice is adopted here. The fifth sub-section considers particles occurring in space, and the final sub-section presents a summary of preferred terminology.

1.2.1 Cosmic Dust

The term was coined by Murray (1883) to denote all classes of extraterrestrial particles discovered in ocean sediments sampled during the HMS Challenger expedition. Cosmic dust included metallic spherules as well as siliceous particles. All particles, which ranged in size from 10 microns to 250 microns, occurred in both recent and ancient sediments located in the deep ocean basin, far from land and from possible sources of industrial contamination (which might well have been much less serious a problem at that time than at present). Furthermore, Murray and Renard (1883, p. 490) noted that the form and character of the spherules were "essentially different" from those collected near manufacturing centers. The metallic particles (also known as cosmic spherules) were black, and were coated with a "magnetic iron oxide" covering an inner portion which gave positive chemical tests for metallic iron, cobalt, and nickel. These elements are rather rare in terrestrial materials, but are common to meteorites. Therefore, Murray and Renard (1883) postulated an extraterrestrial or "cosmic" origin for such particles. They suggested that the dust

particles represented fragments of meteorites which disintegrated upon entering the earth's atmosphere. Unfortunately, Buddhue's definition of "meteoritic dust" (section 1.2.2) is identical to this usage of cosmic dust, and these apparent synonyms have been used indiscriminately by many workers. The writer finds this practice confusing, particularly because reference to original usage of the terms is commonly omitted. Recently, Brunn _et al._ (1955) proposed to call such particles _caudaites_ to distinguish them from other cosmic bodies, but this term did not gain acceptance.

Recently, Krinov (1961) suggested that the term cosmic dust be restricted to those particles which were sufficiently small to settle on the earth's surface without undergoing melting by atmospheric friction. To accomplish this, the particles must be less than about 5 microns diameter. This definition of cosmic dust clearly departs from Murray's original usage of the term. Krinov's definition of cosmic dust is identical with Whipple's usage of the term "micrometeorite" (see below, section 1.2.3).

The writer prefers Krinov's definition of cosmic dust to those offered previously. In a clear, descriptive manner it summarizes the nature of the smaller particles and presents what can be inferred about their origin.

Extremely small particles (about 0.01 micron diameter) encountered by the earth were designated _nanometeorites_ by Hemenway _et al._ (1961). So little is known about these particles that the definition of the term has not been altered. The writer regards these particles as a type of cosmic dust, although future work may require revision of this categorization.

1.2.2 Meteoritic Dust

This term was employed by Buddhue (1950) to describe spherical particles composed of both metal and glass, cindery fragments, and angular grains. It implied that such material originated from disintegration and/or partial fusion of meteoroids during their passage through the earth's atmosphere. The similarity of this definition of meteoritic dust with Murray's usage of cosmic dust is apparent. However, the writer does not favor use of two names for the same material.

Krinov (1959) suggested that meteoritic dust be redefined as the globules and angular, deformed, particulate-matter which occurs at the sites of larger meteoritic falls. This definition is preferred by the writer.

1.2.3 Micrometeorite

This term was coined by Whipple (1949) to describe very small meteoroids which radiate energy fast enough so that upon entering the earth's

atmosphere they do not reach their melting point. The form of these particles would be unchanged and can be considered samples of "interplanetary dust" (section 1.2.5).

Unfortunately, micrometeorite has been used by Vedder (1961), among others, to denote the solid particles encountered by space vehicles. Newspaper accounts of space researches are particularly guilty of this improper usage, which has become popular in spite of the fact that material must reach the earth in order to be considered a meteorite. As Goettleman et al. (1961) pointed out, the term "micrometeoroid" should be used to describe particles found in space. In connection with that incorrect usage of Whipple's term, current practice by many workers has expanded it to include all sorts of microscopic extraterrestrial particles, not just the smallest as Whipple intended. It is regrettable that the original definition of micrometeorite should have become so clouded in such a short time. However, because of this confusion, the writer prefers the term cosmic dust for such small particles.

In an attempt to conform to present usage, Krinov (1959) suggested that the term micrometeorite be restricted to small particles having the basic properties of meteorites (i.e. fusion crust, flow marks, etc.). To possess these features the particles must necessarily be larger than 5 microns in diameter. The writer recommends that this definition be adopted; it is precisely implied by the components of the term.

1.2.4 Meteoric Dust

Krinov (1959) coined this term to denote material resulting from melting of a cometary meteor in the earth's atmosphere. Some of the particles resulting from this process are spheroidal, while others are irregular flakes. They have an entirely different chemical and mineralogical composition from the bodies that produced them because of oxidation during flight. Meteors are quite distinct from meteorites, and apparently have had a different origin (Mason, 1962).

The writer has encountered this term rarely in his literature survey. It is a relatively new one, which may account for its limited adoption. A primary reason for its infrequent use may be the difficulty in recognizing the source of particles, so critical to the definition of this term. The parent material of meteors apparently disintegrates in the atmosphere and is either lost or extremely difficult to distinguish from meteorites. Still, the writer regards meteoric dust as a useful term, and recommends its adoption. Perhaps the metallic flakes with amorphous (organic?) attachments that Parkin et al. (1962) recovered are meteoric dust; they appear to be associated with principal meteor showers (Parkin and Hunter, 1962).

1.2.5 Interplanetary Dust

Solid particles of microscopic size occurring in space outside of planetary or solar atmospheres have been known by many names. Recent efforts in space research have contributed to this proliferation of terms, apparently introduced by the whims of independent workers. The occurrence of such material in space is suggested by the names interstellar dust (Herzberg, 1954), interplanetary dust (Minneart, 1954), galactic dust (Inglis, 1961), primordial dust (Öpik, 1954), zodiacal dust (Kallman, 1954), and zodiacal particles (Whipple, 1954). The particles are apparently concentrated in the plane defined by the sun and orbits of the planets (ecliptic plane).

What can be inferred about the origin of space particles is indicated by the terms cometary debris, planetary debris, and asteroidal fragments.

Present knowledge of solid particles occurring in space is fragmentary and incomplete. The writer prefers a descriptive term, one which informs the reader of particle character and occurrence, and recommends that the term interplanetary dust be adopted for this purpose.

1.2.6 Summary of Preferred Terminology

The writer prefers the following terms to denote microscopic extraterrestrial particles which occur at the surface of the earth or in the earth's atmosphere.

Cosmic dust: microscopic particles small enough to settle on the earth's surface without undergoing melting by atmospheric friction (less than about 5 microns in diameter).

Meteoritic dust: microscopic particles which occur at the sites of larger meteorite falls.

Micrometeorite: microscopic particles having the basic properties of meteorites, including fusion crusts and flow markings (greater than about 5 microns in diameter).

Meteoric dust: microscopic particles resulting from melting of a meteor in the earth's atmosphere.

The writer prefers the term interplanetary dust to denote microscopic particles occurring in space outside the practical limits of the earth's atmosphere.

1. 3. Description of Particles

Identification of microscopic extraterrestrial particles is a difficult task, principally because some terrestrial geological processes and

industrial means produce material generally similar in appearance. Volcanic eruptions, such as that of Kratatoa in 1883, spewed large amounts of dust and ash into the earth's atmosphere. Fredriksson (1961) showed that such volcanic particles were similar in many ways to those of extraterrestrial origin, differing primarily in chemical composition and especially in nickel content. Industrial particles may also be confused with those from space. Handy and Davidson (1953) showed that the particles Thomson (1952) recovered from Iowa snows and believed to be of meteoritic origin were probably from a nearby manufacturing center. These contamination hazards must be considered in each collection of extraterrestrial particles in order to obtain meaningful results; precautions employed to eliminate or control contamination have not been standard throughout the history of this work. The reader is urged to keep this in mind as he considers the following review of particle descriptions.

Microscopic extraterrestrial particles are represented by several different types, as recognized in previous studies. These are described in Table I:1 (Appendix I), which contains eight different classifications of such material taken from the literature. The table shows that most of the particles are spherical in shape, and that their most common constituents are metallic (iron and nickel) and glassy (siliceous). The predominance of spherical particles in these classifications is striking, especially among the varied material of Buddhue's (1950) listing. It is reasonable to suspect that the cause of this super-abundance of spherical particles is their ease of recognition. A smooth, spherical grain is conspicuous in any assemblage of normal, sub-angular to sub-rounded rock fragments, and can be readily distinguished as distinctly different from its neighbors. Moreover, terrestrial geological processes so rarely produce spherical forms that an extraterrestrial origin for such particles is a real possibility. Recognition of non-spherical extraterrestrial particles in juxtaposition with terrestrial rock fragments is many times more difficult, and it is likely that this accounts for the paucity of data for them. In fact, Murray's original classification was limited entirely to spherical particles, as were more recent ones by Skolnick (1961) and Utech (1962).

The several classifications of microscopic extraterrestrial particles, each useful separately in their present forms were employed in the construction of a comprehensive classification of such particles. This is shown in Table I:2 (Appendix I). It was thought that in this way the present investigation could most effectively benefit from the knowledge attained by the previous workers. The aggregate classification is viewed as a working model, which will probably require revision during present research.

The writer classifies most of this material as micrometeorites. The majority of particles are too large to be cosmic dust. Most samples are from localities far removed from known meteorite falls and therefore do not fit the definition of meteoritic dust. The few coated particles may be samples of meteoric dust. Except where specifically noted, however, all material in the comprehensive classification given in Table I:2 is regarded as a type of micrometeorite under the definition shown in section 1.2.6.

1. 4. Size

The sizes of known microscopic extraterrestrial particles vary over a considerable range. The smallest (cosmic dust) particles collected were 0.01 micron in diameter (Hemenway, 1961), while the largest (micrometeorites) were 850 microns in diameter (Skolnick, 1961). These are the extremes of particle sizes investigated. Most particles, however, were less than 250 microns in diameter, and the most frequently occurring sizes were in the narrow range from 1 micron to 60 microns in diameter. A listing of size determinations is presented in Table I:3 (Appendix I).

Graphical representations of size distributions and abundances of particles are shown in Figures 1 and 2. (Appendix I). Figure 1 is a compilation of data from eight surface-based studies of micrometeorites (metallic spherules). While it is apparent that not every investigation of metallic spherules considered particles in the same size group, the particle size distribution found in these studies was of similar character. Each investigator found that the bulk of his sample consisted of smaller particles, with larger particles occurring rarely. This appears to be in general agreement with the theoretical relation proposed by Laevastu and Mellis (1961). It is interesting to note the similarity in abundances of particles resulting from studies of the same size group. Hodge and Wildt (1958), Hodge (1960), and Crozier (1960) found very similar values for particles from 3 to about 20 microns in diameter. Buddhue (1950), Laevastu and Mellis (1955), Hunter and Parkin (1960), Thiel and Schmidt (1961), and Langway (1962) found similar abundances for particles from 10 to 120 microns in diameter. The slight disagreements between these studies will probably be resolved by present researches.

Figure 2 shows a compilation of size distributions for glassy micrometeorites, compiled from two surface-based studies. Preliminary values from the writer's present investigation are included for comparison. The general particle-abundances of the glassy spherules are similar to those for metallic spherules, but the data are too limited to permit further comparisons at this time.

Parkin and Hunter (1962) noted two size groups for "stony" spherules. The smaller particles, less than 60 microns in diameter, were thought to be derived from the breakup of larger spherules due to aerodynamic forces. Whether a similar explanation can be applied to small metallic spherules remains to be demonstrated.

1. 5. Physical Properties

The small size of microscopic extraterrestrial particles has made determinations of their physical properties quite difficult. What little is known or inferred about these properties is summarized in Table I:4 (Appendix I). These data present only a general idea of the physical character of micrometeorites. Furthermore, it is difficult to compare and evaluate values obtained by different workers, for often the methods used and error limits of the values obtained were not reported. The data

suggest, however, that the specific gravity and refractive indices of the glassy particles place them in the realm of rock-forming minerals and meteorites. The metallic spherules are most similar to metallic meteorites.

1. 6. Chemical Composition

Relatively few chemical analyses of microscopic extraterrestrial particles have been performed. It is likely that the small size of the particles has hindered progress in this direction. However, Castaing and Fredriksson (1958) showed that the x-ray microprobe offers much promise in discovering the composition of micrometeorites. This method of analysis is becoming increasingly important for such studies.

It is clear from the limited data presented in Table I:5 (Appendix I) that most previous analyses were done on metallic spherules. In many cases, nickel was observed to be present in the particles. These data, which most clearly resemble those for large, metallic meteorites, are cited as indicative of an extraterrestrial origin.

1. 7. Occurrence

Locations where microscopic extraterrestrial particles have been collected on the earth are listed in Appendix II. It can be seen from this listing that micrometeorites have been recovered from positions which differ widely in latitude and longitude. In fact, they have been found literally around the world and from pole to pole. There appears to be no systematic relation of particle occurrence to geographical position on the earth's surface. Therefore, the assumption made by many workers in estimating the annual deposit of this material, namely, that the particles fell over the entire surface of the earth, is not prohibited.

On the basis of astronomical observations, the presence of solid particles in interplanetary space has been suspected for some time. Many studies of the character of solar light have suggested that bands of "obscuring matter" or dust particles may occur in scattered localities throughout our galaxy. Light absorption studies have showed that interplanetary dust is indeed present in space, and that it tends to be concentrated in the plane of the ecliptic, i.e., the plane defined by the sun and the orbits of the planets. The reflection of sunlight from such particles was postulated as the cause of the zodiacal light, hence the name zodiacal dust was applied to these particles.

Recently, rocket and satellite observations have suggested that interplanetary dust occurs in rather high concentrations in the space near the earth. Beard (1959) noted that interplanetary dust is distributed in space as the inverse three-halves power of its distance from the sun. He further stated that all particles in the vicinity of the earth

will have their orbits materially affected by the earth's pull, and thus may eventually encounter the earth's atmosphere (as micrometeorites?). The dust would be attracted toward the ecliptic plane by the gravitational pull of the earth's mass, and would form dust blanket around the earth with a density of about 10^{-15} particle per cubic centimeter. This is about 1000 times the density of interplanetary dust in normal regions of space as determined by astronomical observations. Dole (1962) reported calculations which show that a steady-state dust cloud of such concentration can be produced through gravitational concentration of low-velocity particles.

On the other hand, Whipple (1961), while agreeing that a high concentration of interplanetary dust occurs near the earth, suggested that the concentration falls off roughly as the inverse 1.4 power of the distance from the earth's surface, to a distance of approximately 100,000 km. Dole's (1962) calculations suggested that concentration decreases as the inverse 1.66 power of the distance from earth.

Goettleman _et al_. (1961) apparently held a view similar to Whipple's. They postulated the existence of a _meteoroid halo_ or belt of relatively high, constant particle density surrounding the earth, but extending only to an altitude about 4000 km above its surface. Beyond that level they envisioned a region of lower particle density.

Another view is held by Singer (1961), who proposed that there is a maximum in dust concentration at about 2000 to 3000 km above the earth's surface, giving rise to a _dust shell_. Mirtov (1962) also postulated a dust shell, but placed the maximum at only 100-200 km above the earth's surface. The increase was thought to amount to only a few times the value of the dust concentration in interplanetary space, rather than the factor of 1000 given by Beard (1959).

The work of McCracken, Alexander, and Dubin (1961) does not support the dust cloud or dust shell interpretations cited above. They maintained that there is no discernible dependence of the spatial density of dust particles on altitude. Further, they stated that if a high concentration of dust particles exist, measurements of dust concentrations at very large distances from the earth would be necessary to confirm its presence. In other words, they maintained that the limited data currently available do not permit recognition of a dust cloud or dust shell around the earth.

Recently, however, Alexander (1962) reported measurements of interplanetary dust conducted by the Mariner II space probe. These indicated that 10^4 times fewer particles were encountered in space between Earth and Venus than were detected by satellites nearer the earth. The preliminary data thus suggested that there is a concentration of interplanetary dust near the vicinity of Earth. Its exact character is still unknown.

The diverse views mentioned briefly above are eloquent testimony of the amount of effort being expended in the study of interplanetary dust as a part of the space environment of the earth.

A compilation of several available estimates of the concentration of interplanetary dust in outer space is given in Table I:6 (Appendix I).

The table shows that most workers consider interplanetary dust to be present in space in concentrations ranging from 10^{-20} gm/cm^3 to 10^{-24} gm/cm^3. Fewer values are available for the concentration of particles in space near the earth, and these are in less close agreement, ranging from 10^{-14} gm/cm^3 to 10^{-22} gm/cm^3. Present information does not permit selection of single values for the concentration of interplanetary dust either in space or in the vicinity of the earth.

The average cumulative-mass distribution curve of interplanetary dust near the earth is shown in Figure 3. These data, obtained from rocket, satellite, and space-probe measurements, are consistent with surface-based studies in that the smallest particles were found to occur most frequently.

1. 8. Annual Deposit

Microscopic, extraterrestrial particles have been collected from sediments (including ice) and from rocks of many different ages representing many different geographical positions. It appears that virtually the entire earth has received deposits of such material from the present day back through geological time at least to the Ordovician period (Crozier, 1960). Particle deposits probably occurred even earlier in the earth's history.

Many terrestrial studies of the rate of particle deposition have been conducted. Several geological and glacialogical estimates of the rates of accumulation of sediments and ice are valuable tools in this work. Knowledge of the amounts of sediments and snow which were deposited in one year, together with determinations of the mass of microscopic extraterrestrial particles occurring in individual layers, have been used by previous workers in estimating the annual deposit of these particles on the surface of the earth. These estimates are listed in Table I:7. The table shows that the estimates of annual particle deposit vary widely, from 8 metric tons per year (Buddhue, 1950) to 3,100,000 metric tons per year (Kreiken, 1959). Part of this enormous disparity in values may be traced to the fact that not all estimates were based on studies of the same types of particles. For example, one value may be obtained from study of metallic spherules (Bruun _et al_., 1955), another from the total influx of all dust particles (Öpik, 1956). Still, serious disagreement exists among estimates for supposedly identical material. For example, estimates of the influx rate of black, magnetic spherules differ by as much as a factor of about one million, as in Buddhue's and Kreiken's values.

The problem of selecting even an approximate value for the yearly influx of any microscopic extraterrestrial particles is complicated. There appears, however, to be reasonable agreement among recent estimates of the annual deposit of black, magnetic spherules. Although slightly different sized particles were examined in each case, Crozier (1961,1962),

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Fireman and Kistner (1961), Thiel and Schmidt (1961), and Wright and Hodge (1962) estimated the annual deposit of metallic spherules to be approximately 200,000 metric tons. At the present stage of investigation, the slight disagreements among these workers should not be discouraging.

An apparent seasonal variation in the deposition of black, magnetic spherules has been observed. Kizilirmak (1954) noted that fewer particles were deposited in Ankara, Turkey in the month of February, while maximum numbers of particles were recovered in July. His work was continued by Süslü (1956), who observed similar variations and found much greater numbers of particles than were collected in the earlier study. Kreiken (1959) summarized the earlier Turkish observations, and suggested that the numbers of particles collected were related to periods of meteoric activity, but that they lagged about one month behind that phenomenon. Parkin and Hunter (1962) reported a much shorter lag-relationship of particle occurrence to meteor showers. Maxima of particle occurrence were observed only a few days after meteor showers. Crozier (1962) reported that, in general, maximum numbers of spherules were collected in spring and summer months. Both Crozier's New Mexico station and the site of Turkish observations are situated on about the same latitude, although on opposite sides of the globe. The fact that similar effects were observed at each place suggests that their cause may have been world-wide. Parkin et al. (1962) also noted greater amounts of particles in the summer months. Hasegawa (1959) reported that Japanese workers found conflicting seasonal variations of particle deposition. Morikubo found largest numbers of particles during August and September, as did the workers cited above. On the other hand, Yamada found largest numbers of particles in January and February, when all other workers reported fewest particles. This disagreement in Japanese data is difficult to explain, unless it has been caused by proximity to nearby industrial centers.

All sites where seasonal variations in particle deposition have been observed are located in the northern hemisphere. It would be valuable to know whether similar seasonal variations in particle deposition occur in the southern hemisphere. In particular, it would be important to determine whether or not any seasonal variations in the southern hemisphere occur at the same time of year as those observed in the northern hemisphere.

The cause of seasonal variation in particle deposition is presently obscure. It may be related to principal meteor showers as suggested. However, Gallagher and Eshelman (1960) have shown that the earth is constantly immersed in minute meteor showers. Hence the validity of the simple explanation offered by previous workers remains to be demonstrated. Furthermore, meteorological influences on particle deposition are poorly known. The extent to which particle deposition may be controlled by such factors requires study.

Crozier (1962) showed that the cumulative rate of particle deposition in New Mexico was greatest for smaller particles, decreasing sharply for larger ones. On the other hand, data for Antarctic spherules show a greater increment of mass per diameter interval for larger spherules (Schmidt, 1963), (Fig. 4). These results may have been influenced by the latitude

of the different sampling sites and/or by the earth's magnetic field. However, Öpik (1956) and Singer (1958) have concluded that a dust particle in outer space would be electrically charged. As a result, the earth's magnetic field would have little effect on the path of the particle, particularly at meteoric speeds. However, as Parkin and Hunter (1962) pointed out, the situation may be "radically altered" if ionized interplanetary gas exists. This would produce a strong interaction between the gas and the particle. Fine dust may be brought to rest with respect to the gas, and drift with it, perhaps to be concentrated at the auroral zones. This process would be assisted if the particles were travelling at relatively low velocities, as suggested by Dole (1962). These divergent views will be tested by new investigations of Antarctic samples in progress at the writer's laboratory.

Measurements of microscopic, extraterrestrial particles by artificial earth-satellites have been conducted from the beginning of the space age. These studies have also yielded estimates of annual particle deposition. However, the devices employed on satellites to detect particles were unable to differentiate between compositional types, so these annual deposition values represent the total influx of all such particles to the earth. As Table I:7 shows, the satellite estimates are in remarkable agreement, indicating that slightly more than 10^6 metric tons of microscopic particles of all types are deposited on the earth each year. It is interesting to note that the annual deposit of black, metallic (magnetic) spherules, estimated from terrestrial sources to be approximately 10^5 metric tons, is about 10 percent of the total particle influx. The significant fact about this percentage of microscopic, metallic particles is that it is in excellent agreement with the abundance of macroscopic metallic meteorites; Krinov (1961) noted that only about 6 percent of known falls of large meteorites were metallic. The apparent analogy in the occurrence of metallic particles and metallic meteorites is another similarity among these materials. However, as Crozier (1961) cautions, a large fraction of particles intercepted by satellites may be in orbit around the earth, and may not be deposited.

1. 9. Theories of Origin

The data suggest that many microscopic, extraterrestrial particles are similar to larger meteorites in appearance, physical properties, chemical composition, and abundance. These relationships have weighed heavily upon theories of particle origin.

Murray and Renard (1883) suggested that the black, metallic spherules they recovered from oceanic sediments were produced by "combustion" and "fragmentation" of metallic meteorites during their passage through the earth's atmosphere. Buddhue (1950) proposed a simiiar hypothesis. He reasoned that the spherical shapes and highly polished surfaces indicated that the particles had been melted and suggested that meteorite ablation yielded metallic micrometeorites. The writer interprets Buddhue's remarks on particle origin as including siliceous spherules, although they were

not specifically mentioned. However, Bruun et al. (1955) held a similar view, and suggested that silicate spherules were produced by ablation of stony meteorites. Castaing and Fredriksson (1958) adopted the ablation hypothesis as an explanation of the oxidized particle rim and distribution of iron and nickel in the particles. The argument is impressively supported by the data of quenching experiments which Bruun et al. (1955) conducted with artificial iron-nickel-carbon melts. Molten metal was poured into a container of water from a height of about one meter, and black spherules identical to those found in oceanic sediments were produced. Clearly, the experimental work suggested that spherules could be produced through meteorite ablation. However, Parkin and Hunter (1962) showed that even if the entire mass of each meteorite entering the earth's atmosphere was converted to spherules, this amount would be insufficient to produce the number of spherules which fall to earth each year. The hypothesis is thus inapplicable to the majority of spherules. However, there is little doubt that meteoritic ablation takes place, as evidenced by the fusion crust and globules at the place of fall of the Sikhote-Alin meteorite, among others. The writer therefore accepts the ablation theory in explanation of the origin of meteoritic dust.

Parkin and Hunter (1962) suggested that most spherules are produced by the oxidation and melting of minute fragments of solid bodies as they enter the atmosphere, without much evaporation occurring. The writer concurs in this view, and considers these materials micrometeorites.

The origin of meteoric dust is probably related to ablation of cometary meteors in the earth's atmosphere. Whipple (1950, 1955) regards comets as a conglomeration of ices of water, ammonia, methane, and carbon dioxide together with solid debris of a meteoritic nature. Friction with the earth's atmosphere would cause the volatile ices to evaporate, freeing the solid particles to fall to earth. Perhaps the amorphous coatings on metallic flakes represent samples of the cometary ices. This hypothesis is supported by the work of Parkin and Hunter (1962), who found that metallic flakes were apparently related to meteoric activity; greater numbers of metallic flakes were collected following meteor showers. They suggested that the metallic flakes were embedded in a mass of oils or waxes of low volatility, which evaporate and cool the flakes during retardation in the earth's atmosphere. As the waxes melt the metallic flakes would be freed in the meteoric wake.

The production of cosmic dust and interplanetary dust is more speculative than the apparent origins of the above materials. Probably, evaporation of cometary nuclei as they approach the sun releases solid particles into space. Whipple (1955) estimated that about 30 tons per second of meteoritic material is continuously contributed to space by this mechanism. However, only about 3.5 tons of the total are added effectively to space, because many particles are lost through the actions of the interstellar wind, collisional destruction, attraction by Jupiter, and by the Poynting - Robertson effect. The latter is a retardation of the orbital motion of particles by the "braking" effect of solar radiation, which causes a slow,

secular decrease in the semi-major orbital axis of any small body, causing it to ultimately fall into the sun.

Whipple's icy comet-hypothesis appears to avoid the difficulty posed by the Poynting - Robertson effect, among the others, by suggesting a continuous source of interplanetary dust particles. In other words, at least as much solid material (interplanetary dust) is thought to be added to interplanetary space by the evaporation and/or disintegration of cometary nuclei as is lost to the sun by the action of the Poynting - Robertson effect, and by other processes mentioned which might cause a decrease in its concentration.

Similar views are held by van de Hulst (1955). He estimated that interplanetary dust particles are at low temperature, (10 to 40° K) and that they consist of ices of water, ammonia, methane, and metal impurities.

Along the same lines Squires and Beard (1960) noted that surface evaporation of comets takes place as these bodies approach the sun. The material present is thus lost from the comet, and presumably forms its tail. Comets are thought to lose a considerable fraction of their mass during one flight. The formation of the dust particles themselves, however, is poorly understood at present.

At least part of interplanetary dust may originate in the asteroidal belt through collisions between asteroids, meteoroids, and sporadic bodies. The asteroidal belt is a region of space between the orbits of Mars and Jupiter in which several hundred celestial bodies of varying size are situated. Many believe that these were produced through the explosive breakup of a former planet (Parkin and Hunter, 1962). Internal collisions among the fragments of this process could be a continuous source of dust particles (Piotrowski, 1953). However, Parkin and Hunter (1962) maintained that such materials would be "confined" to the asteroidal belt, with only a small percentage sufficiently deviated by collisions to move in inclined orbits.

In addition to internal collisions in the asteroidal belt, it is possible that some dust particles may represent fragments of the lunar surface, dislodged by meteoroid or cometary impact (Gault, 1962; O'Keefe, 1962, personal communications). However, the character of such material and the amount contributed from this source are imperfectly known.

It was once thought that interplanetary dust particles were remnants of the original dust cloud from which our solar system originated. However, it has been shown by Öpik (1955) and by Wyatt and Whipple (1950) that even if our solar system did originate in this way, most smaller particles would have been swept into the sun by the Poynting - Robertson effect. It thus appears unlikely that interplanetary dust particles encountered by contemporary space vehicles could represent original galactic dust.

Another source of interplanetary dust might be intergalactic clouds of dust encountered periodically by our solar system as it drifts through space (Best, 1960). The existence of such clouds in intergalactic space has been postulated because astronomical studies of the light emitted by stars and by the sun show that it has been scattered, absorbed, and polarized. While the possibility that such material may contribute to the interplanetary dust content of our solar system cannot be ignored, present information is too limited to permit serious evaluation of the proportion of interplanetary dust which might be supplied by this source.

A summary of the sources of microscopic, extraterrestrial particles as indicated by the above discussion is presented in Table I:8 (Appendix I). Robey's (1959) general scheme was adopted in constructing this table, although it was altered somewhat from the original form to include the preferred terminology used in this survey. The conclusions about particle-origin which this table presents are tentative, however, and subject to revision. More definitive hypotheses can be formulated only when the results of quantitative chemical and physical studies of the particles become available.

PART 2

COMPILATION OF DATA

APPENDIX I

DATA FOR MICROSCOPIC EXTRATERRESTRIAL PARTICLES COMPILED FROM PREVIOUS STUDIES

TABLE I: 1

CLASSIFICATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

		Size (microns)
A. Murray and Renard (1883)		
1.	Black, magnetic spherules $\pm$ metallic nucleus	60-200
2.	Brown-colored spherules, resembling chondrules, with a crystalline surface	60-500
3.	Yellowish or brown spherules, with bronze luster $\pm$ opaque inclusions of magnetite	<500
B. Jung (1883)		
1.	Irregular, amorphous grayish fragments	100-200
2.	Mammillated particles, black and opaque (clusters of minute spheres)	100-200
3.	Fibrous particles	100-200
4.	Black, opaque corpuscles	10-20
5.	Hollow spheres with a tiny, vase-like neck	?
C. Buddhue (1950)		
1.	Irregular, angular fragments	--
2.	Scoriaceous or cindery particles	--
3.	Rounded grains resembling fine black sand (probably terrestrial magnetite)	--
4.	Smooth, black, highly polished perfect spheres of widely varying diameter	20 (mean)
5.	Larger black spheres with less luster and often roughened or pitted	100 (mean)
6.	Silicate spheres which are white, gray, yellowish, brown, and sometimes black. Some are transparent and these usually show bubbles and dark inclusions	--
7.	Hybrid spheres which are mostly type 4, but also include visible areas of glass which is often semi-transparent.	--

D. Bruun, Langer, and Pauly (1955)

		Size (microns)
1.	Reniform, slag-like greyish to greyish brown	100-200
2.	Greyish to greyish brown spheres	100 (mean)
3.	Shiny, black spheres	100-500
4.	Light metallic grey spheres	200-500

E. Hunter and Parkin (1960)

1.	Smooth, black, iron-nickel spherules	20-384
2.	Rough, gray, stony spherules	15-500
3.	Stony-iron spherules	20-100

F. Skolnick (1961)

	Color	Exterior	Magnetic Attraction	Wall	Core
1.	Black	Smooth, faceted, dull, shiny	Weak to strong	Thick	Yes
2.	Steel gray	Smooth, burnished, reticulate	Strong	Thin	None
3.	Mottled black, steel grey	Faceted, inter-grown	Strong	Thick	None
4.	Brown to black	Smooth, rare bubbles	Nonmagnetic	Thick	None

G. Hemenway et al (1961)

		Size (microns)
1.	Black spherules	0.01-1
2.	Irregular particles	0.1-1
3.	Fluffy particles (cosmic dust)	0.1-1

H. Parkin, Hunter, and Brownlow (1962)

1.	Metallic flakes and particles with yellowish, amorphous (organic?) attachments. (meteoric dust)	70x400

I. Utech (1962)

1.	Steel gray, rough surfaced spherules	80-120
2.	Black, smooth, shiny spherules	80-120
3.	Steel gray spherules	<1500

TABLE I: 2

COMPREHENSIVE CLASSIFICATION OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

	Description	Size (microns)	Source
1.	Black, magnetic spherules with or without metallic nuclei	200	Murray and Renard (1883)
a.	Black, smooth, highly polished perfect spheres	200 20-38	Buddhue (1950) Jung (1883) Skolnick (1961) Hunter and Parkin (1960)
b.	Black, smooth spheres of <u>COSMIC DUST</u>	0.01-1	Hemenway (1961)
c.	Shiny, black, hollow spheres with or without vase-like neck	100-500	Jung (1883) Bruun *et al* (1955) Fredriksson (1961) Skolnick (1961)
d.	Larger black spheres with less luster, often roughened or pitted, light metallic gray color	100	Buddhue (1950) Bruun *et al* (1955) Skolnick (1961)
2.	Mammillated particles, black and opaque clusters of minute spheres	100-200	Jung (1883)
a.	Mottled black, steel gray, faceted intergrown	?	Skolnick (1961)
3.	Silicate spheres which are white, gray, yellowish, brown, and sometimes black. Some transparent, usually with bubbles and dark inclusions (magnetite or metallic iron)	70-500	Murray and Renard (1876) Buddhue (1950) Bruun *et al* (1955) Skolnick (1961)
a.	Hybrid spherules: part semi-transparent glass, part metallic	100 20-100	Buddhue (1950) Hunter and Parkin (1960)
4.	Irregular, angular fragments	100-200	Jung (1883) Buddhue (1950)
a.	Irregular fragments of <u>COSMIC DUST</u>	0.1-1	Hemenway (1961)
b.	Stony spherules	15-500	Hunter and Parkin (1960)
5.	Scoriaceous or cindery particles	100	Buddhue (1950)
a.	Reniform, slag-like grayish to grayish brown particles	100-200	Bruun *et al* (1955)
6.	Fibrous particles	100-200	Bruun *et al* (1955)
7.	Metallic particles with amorphous (organic?) coatings (<u>METEORIC DUST</u>)	70x400	Parkin, Hunter and Brownlow (1962)
8.	Fluffy particles of <u>COSMIC DUST</u>	0.1-1	Hemenway (1961)

TABLE I: 3

SIZE OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

(After Buddhue, (1950) and Hodge et al, (1961))

Investigator	Date	Size (microns)	Source
Nordenskiold	1874	250	snow
Murray	1883	200-500	deep sea sediments
Silvestvi	1880	80-100	"dust fall"
Wulfing	1890	100-200	snow
Jung	1883	100-200	snow
Nininger	1941	90	rain
Landsberg	1947		air
Buddhue	1950	1-120	rain
Thomsen	1953	8-80	snow
Ahnert	1954	100-200	rain
Kizilirmak	1954	1-100	rain
Bruun et al	1955	200-500	deep sea sediments
de Jager	1955	10	zodiacal light
Kallman	1955	1-10	zodiacal light
Laevastu and Mellis	1955	10-230	air
Levin	1955	10	meteor astronomy
Minneart	1955	<350	zodiacal light
Stromgren	1955	1-10	light scattering
van de Hulst	1955	0.8-1	light scattering
Whipple	1955	0.1	meteor astronomy
Fredriksson	1956	35	air
Stoiber	1956	10-340	ice island T-3
Yavnel	1957	30-60	meteorite impacts
Hodge and Wildt	1958	3-15	air
Kolomensky and Yudin	1958	40-200	meteorite crust
Beard	1959	1-5	meteor astronomy
Hasegawa	1959	5-50	air
Hibbs	1959	"several microns"	- - -
Nishibori and Ishizaki	1959	5-60	Antarctic ice
Parkin and Hunter	1959	5-35	air
Yagoda	1959	20-40	air
Best	1960	10-100	light scattering
Crozier	1960	5-35	sediments
Krinov	1960	3-800	air, snow, sediments
Hunter and Parkin	1960	15-500	ocean sediments
Pettersson	1960	30-250	deep sea sediments
Fredriksson	1961	30-100	air
Hemenway et al	1961	0.01-1	high altitude balloons
Hodge	1961	3-30	air
Hunter and Parkin	1961	14-650	Tertiary rock
Skolnick	1961	50-850	sedimentary rock
Soberman et al	1961	0.1-1	high altitude rockets
Thiel and Schmidt	1961	15-180	Antarctic snow
Crozier	1962	5-50	air
Langway	1962	5-160	Greenland snow
Newkirk and Eddy	1962	0.1-3	high altitude coronagraph

TABLE I: 4

PHYSICAL PROPERTIES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Investigator	Date	Particle Type	Specific Gravity	Refractive Index	Magnetic Attraction
Nordenskiold	1870	glassy	2.63	--	--
Silvestri	1880	yellow spherule	2.92	--	--
Buddhue	1950	metallic spherules	4.422-5.535	--	--
Buddhue	1950	glassy spherules	--	1.524-1.560	--
Buddhue	1950	glassy spherules	--	1.530-	--
Thomsen	1953	metallic spherules	4*	--	--
Laevastu and Mellis	1955	metallic spherules	5.2*	--	--
Bruun _et al_.	1955	silicate spherules	--	1.63-1.66	--
Hodge and Wildt	1958	metallic spherules	4*	--	--
Hasegawa	1959	metallic silicate	4.42 avg.	1.524-1.560	present
Skolnick	1961	metallic spherules	--	--	strong
Thiel and Schmidt	1961	metallic spherules	5.18*	--	--
Parkin, Hunter and Brownlow	1962	amorphous coating	--	1.540-1.549	--

*Adopted density

TABLE I: 5

CHEMICAL ANALYSES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES COMPILED FROM SOURCES INDICATED

Investigator	Date	%Fe	%FeO	$\%Fe_2O_3$	%Ni	%NiO	$\%SiO_2$	%Co	%Cu
Herman	1825	90	--	--	--	--	--	--	--
Nordenskiold	1883	92.3	--	--	7.6	--	--	--	--
Buddhue	1950	--	35.5	64.2	--	tr	--	--	--
		--	--	89.4*	--	tr	--	--	--
		--	--	87.3*	--	tr	--	--	--
Thomsen	1953	--	--	72	--	--	28	--	--
Hasegawa	1956	--	--	89*	--	tr	--	--	--
Smales *et al*	1958	10-240+	--	--	0.29-3.9+	--	--	0.05-0.31+	0.0006-0.53+
Castaing and Fredriksson	1958	68.6	--	--	30.1	--	--	1.5	--
		44.4	--	--	53.5	--	--	1.8	--
	(center)	57	--	--	20	--	--	--	--
	(rim)	75	--	--	0.5	--	--	--	--
	(center)	40	--	--	24	--	--	--	--
	(rim)	70	--	--	1	--	--	--	--
Yagoda	1959	+Fe	--	--	+Ni	--	--	--	--
Hunter and Parkin	1960	+Fe	--	--	up to 70% in nucleus	--	--	--	--
Fireman and Kistner	1961	90	--	--	tr	--	--	--	--
Fredriksson	1961	55	--	--	0.2	--	--	--	--
Riggs *et al*	1962	(Ni/Fe ratio) = 0.1 - 2.0							

*total iron as Fe_2O_3

+in mg

TABLE I: 6

ESTIMATES OF THE CONCENTRATION OF

INTERPLANETARY DUST IN OUTER SPACE

Investigator	Concentration (g/cm^3)	Remarks
Greenstein (1937)	10^{-21}	near ecliptic plane
Allen (1947)	10^{-23}	space near earth
van de Hulst (1947)	10^{-21}	spectral studies
Buddhue (1950)	10^{-28}	space
Pettersson and Rotschi	10^{-21}	ocean sediments
Lebidinsky (1955)	10^{-22}	space
Levin (1955)	10^{-23}	space
Minneart (1955)	10^{-15}	near earth
Siedentopf (1955)	$10^{-20 \text{ to } 22}$	space
Stromgren (1955)	10^{-26}	space
van de Hulst (1955)	10^{-21}	near ecliptic plane
Beard (1959)	10^{-15}	near earth
Best (1960)	10^{-27}	zodiacal dust
Hibbs (1959)	$10^{-10 \text{ to } -11}$	near earth
Brown (1960)	10^{-17}	near earth
Dubin (1960)	$10^{-20 \text{ to } 22}$	near earth
Hawkins (1960)	10^{-24}	space
Whipple (1960)	10^{-20}	near earth
Beard (1961)	10^{-18}	space
Beard (1961)	10^{-15}	near earth
Singer (1961)	10^{-21}	near earth
Dubin and McCracken (1962)	10^{-20}	near earth

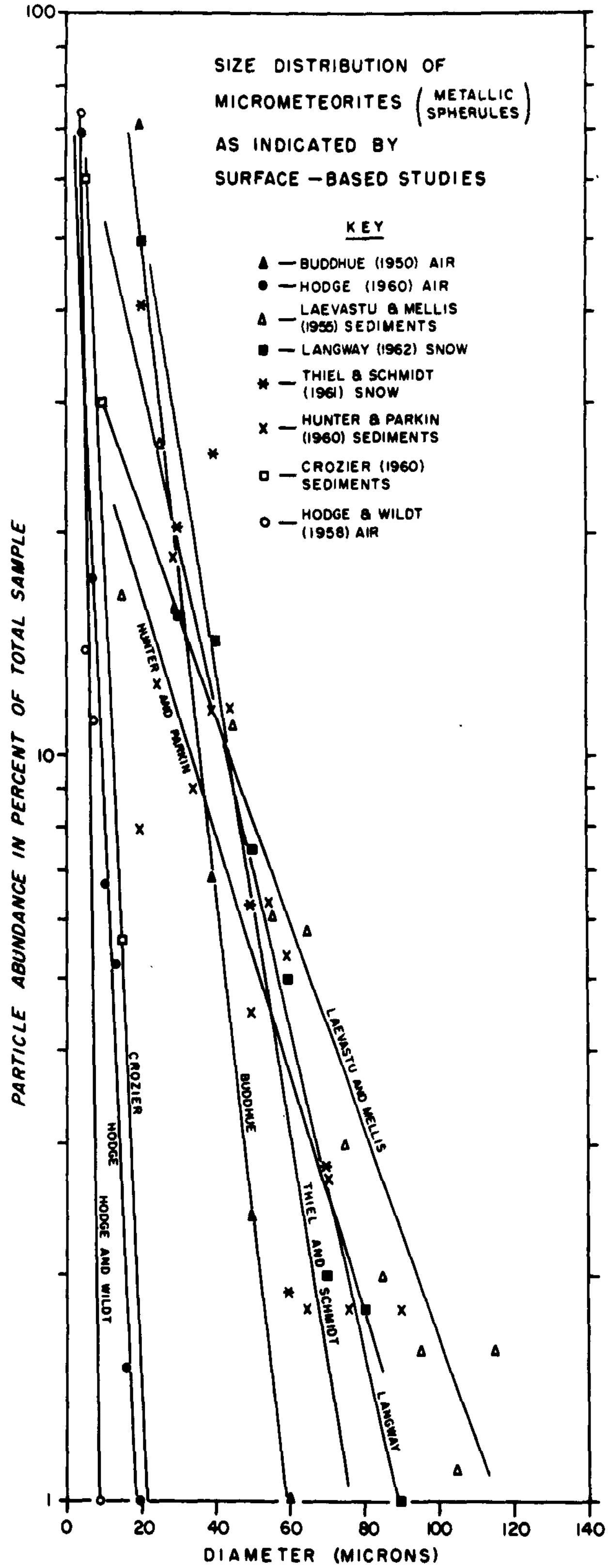
TABLE I: 7

ESTIMATES OF THE ANNUAL DEPOSIT OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES

Investigator	Annual Deposit Metric Tons	Source
Buddhue (1950)	8	Murray's black spheres
Bruun *et al*. (1955)	30	raking ocean floor with magnetic rake
Laevastu and Mellis (1953)	125	deep sea sediments adopted density 5.2
Opik (1956)	170	from Laevastu and Mellis, assuming density 7.8
Watson (1941)	560	meteors
Wylie (1935)	1560-3120	meteors
Pettersson (1960)	3,300	Mediterranean sediments
Pettersson and Fredriksson (1958)	2,400-5,000	Pacific sediments adopted density 5
Watson (1939)	10,000	meteors
Astapovich (1958)	16,000	meteoritic dust
Fireman and Kistner (1961)	30,000-300,000	Ni-bearing dust
Buddhue (1950)	129,000	magnetic dust
Crozier (1961)	90,000	magnetic spherules
Crozier (1960)	150,000	black, magnetic spherules
Crozier (1962)	160,000	black, magnetic spherules >5 microns
Thiel and Schmidt (1961)	184,000	spherules in ice, adopted density 5.18, >15 microns
Wright and Hodge (1962)	200,000	spherules from air
Opik (1956)	250,000	total meteoritic dust
Fesenkov (1960)	365,000	micrometeorites
Hodge and Wildt (1958)	500,000	black spherules adopted density 4
Mayne (1956)	1,825,000	He measurements

TABLE I: 7 (con't)

Investigator	Annual Deposit Metric Tons	Source
Thomsen (1953)	2,000,000	black spherules adopted density 4
Kreiken (1959)	3,100,000	black spherules
de Jager (1955)	365,000 (10^3 tons/day)	zodiacal cloud
Best (1960)	7,300	meteors >0.1 mm
Dubin (1960)	3,650,000 (10^4 tons/day)	satellite 1958 Alpha
Fesenkov (1960)	3,650	zodiacal light
LaGow & Alexander (1960)	3,650,000 (10^4 tons/day)	satellites 1958 Alpha 1959 Eta
Whipple (1960)	3,650,000 (10^4 tons/day)	
McCracken & Alexander (1961)	3,650,000 (10^4 tons/day)	satellite 1960 Xi
Mirtov (1962)	1,825,000-3,650,000 (5,000 - 10,000 tons/day)	satellites



SIZE DISTRIBUTION OF
MICROMETEORITES (METALLIC SPHERULES)
AS INDICATED BY
SURFACE-BASED STUDIES
KEY
▲ — BUDDHUE (1950) AIR
● — HODGE (1960) AIR
Δ — LAEVASTU & MELLIS (1955) SEDIMENTS
■ — LANGWAY (1962) SNOW
✱ — THIEL & SCHMIDT (1961) SNOW
X — HUNTER & PARKIN (1960) SEDIMENTS
□ — CROZIER (1960) SEDIMENTS
○ — HODGE & WILDT (1958) AIR
HUNTER X AND PARKIN
LAEVASTU AND MELLIS
CROZIER
HODGE
HODGE AND WILDT
BUDDHUE
THIEL AND SCHMIDT
LANGWAY
PARTICLE ABUNDANCE IN PERCENT OF TOTAL SAMPLE
100
10
1
0
20
40
60
80
100
120
140
DIAMETER (MICRONS)

Figure 1

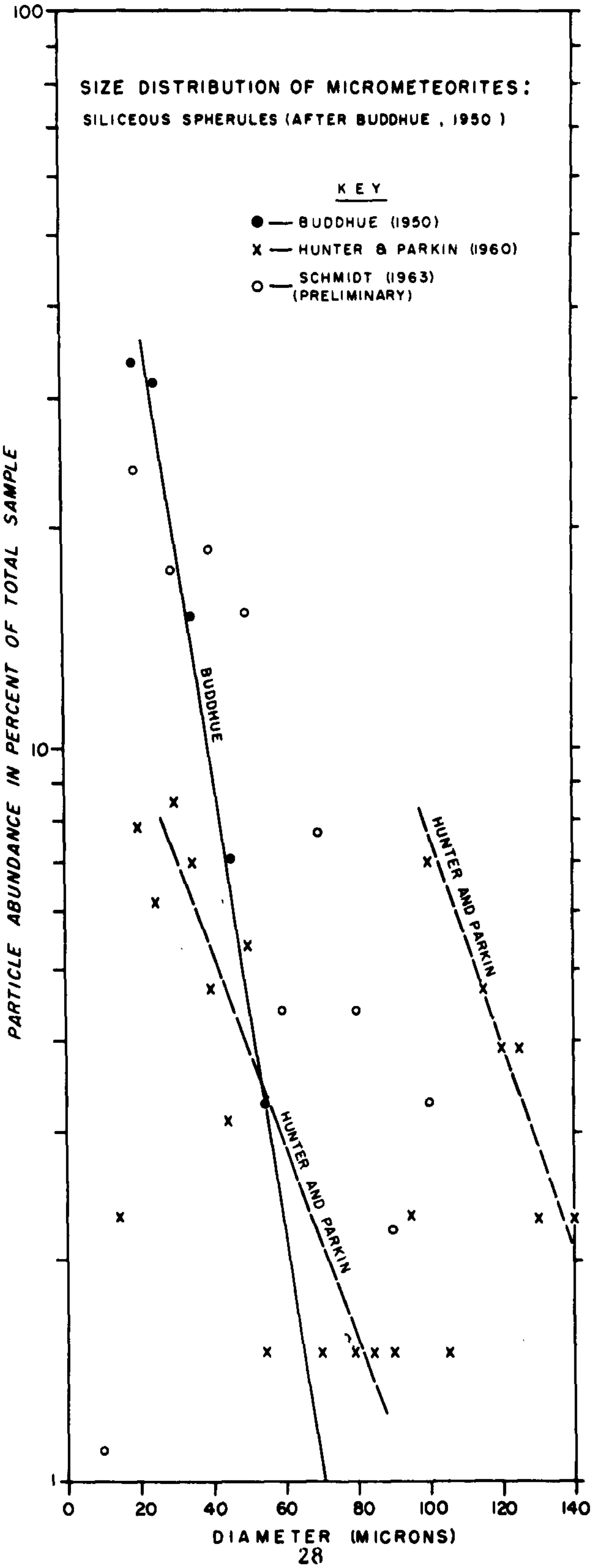
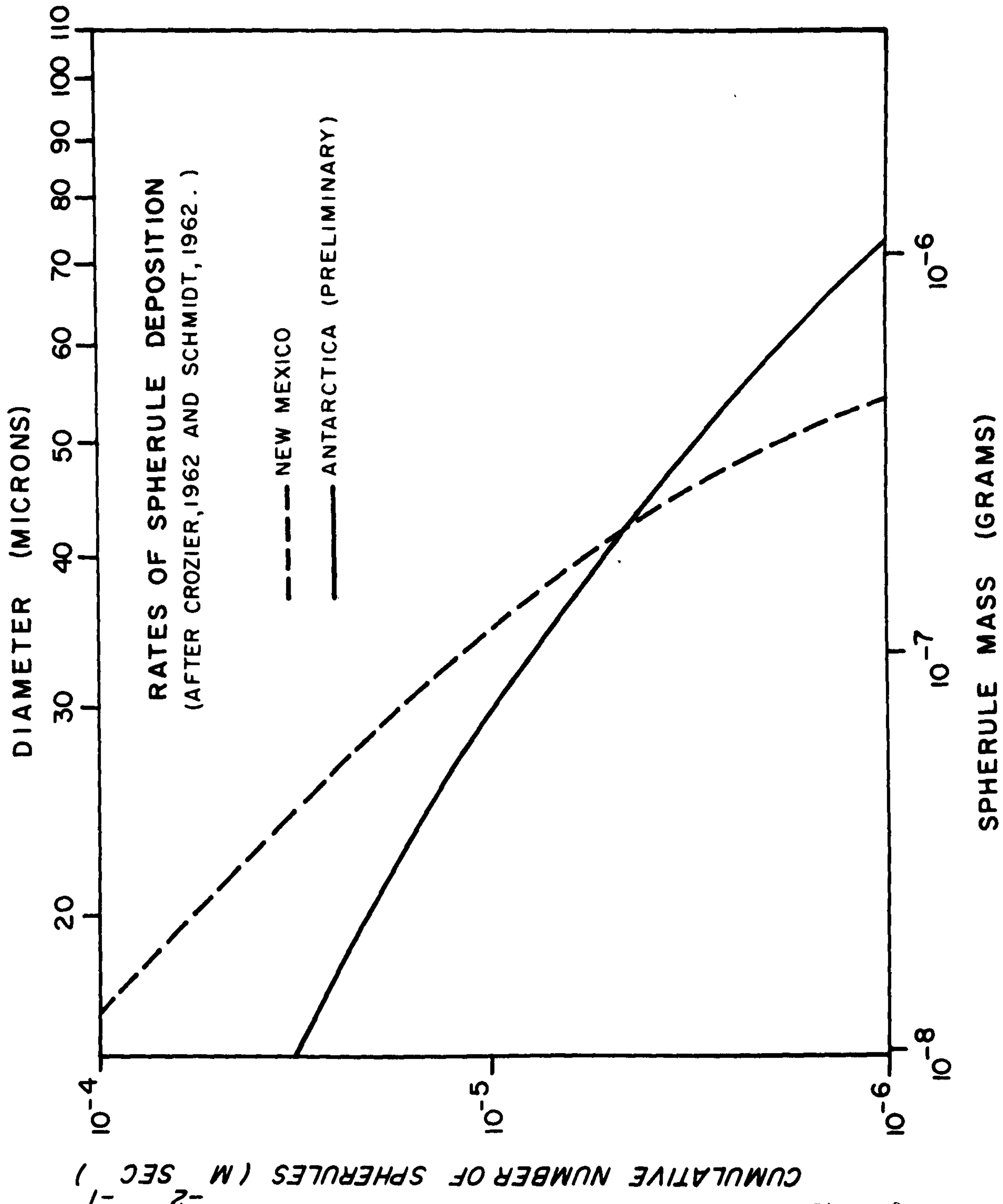

SIZE DISTRIBUTION OF MICROMETEORITES:
SILICEOUS SPHERULES (AFTER BUDDHUE, 1950)
KEY
BUDDHUE (1950)
HUNTER & PARKIN (1960)
SCHMIDT (1963) (PRELIMINARY)
BUDDHUE
HUNTER AND PARKIN
HUNTER AND PARKIN
PARTICLE ABUNDANCE IN PERCENT OF TOTAL SAMPLE
100
10
1
0
20
40
60
80
100
120
140
DIAMETER (MICRONS)

Figure 2



DIAMETER (MICRONS)
20
30
40
50
60
70
80
90
100
110
RATES OF SPHERULE DEPOSITION
(AFTER CROZIER, 1962 AND SCHMIDT, 1962.)
NEW MEXICO
ANTARCTICA (PRELIMINARY)
SPHERULE MASS (GRAMS)
10^{-8}
10^{-7}
10^{-6}
10^{-4}
10^{-5}
10^{-6}
CUMULATIVE NUMBER OF SPHERULES ($M^{-2}SEC^{-1}$)

Figure 3

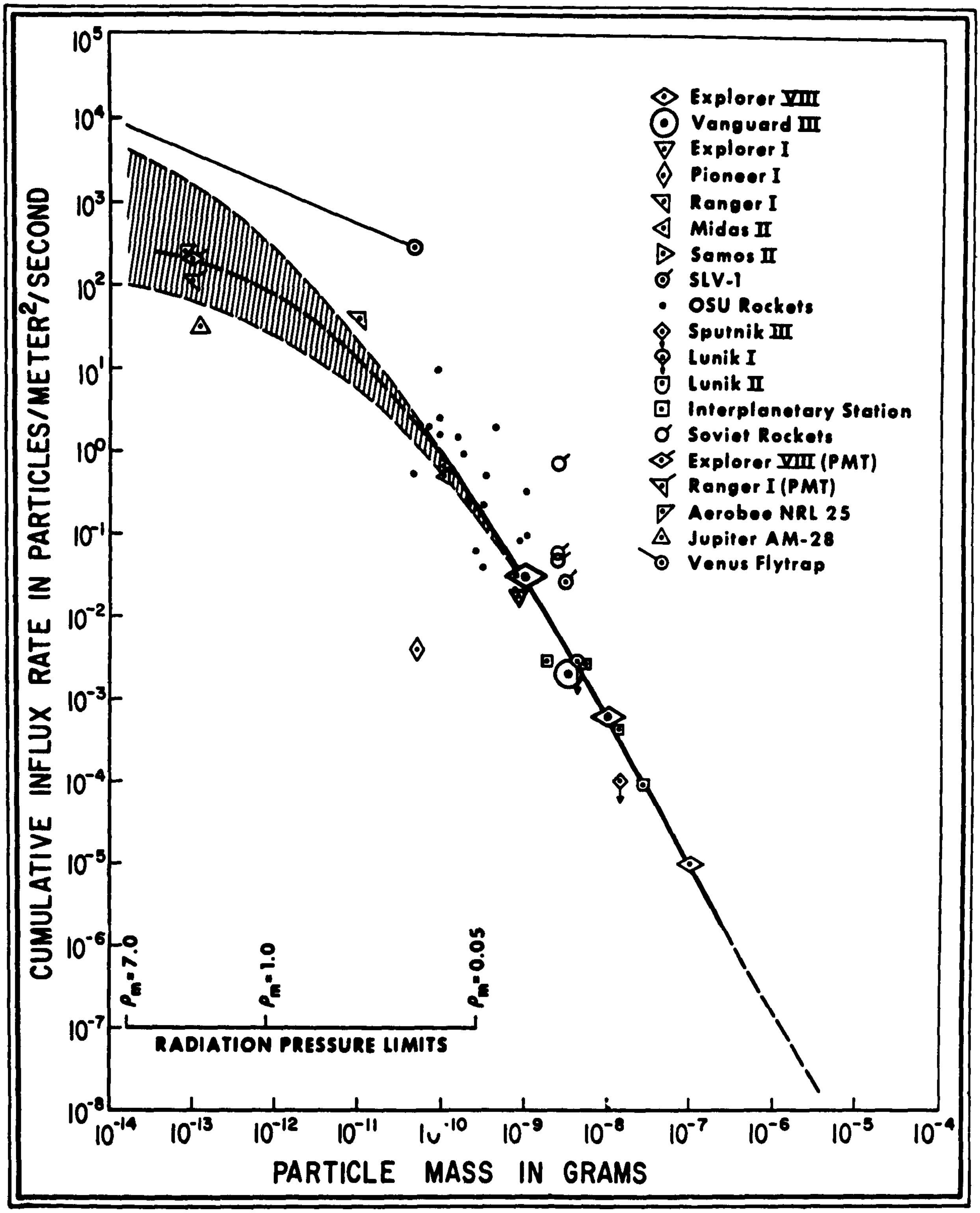
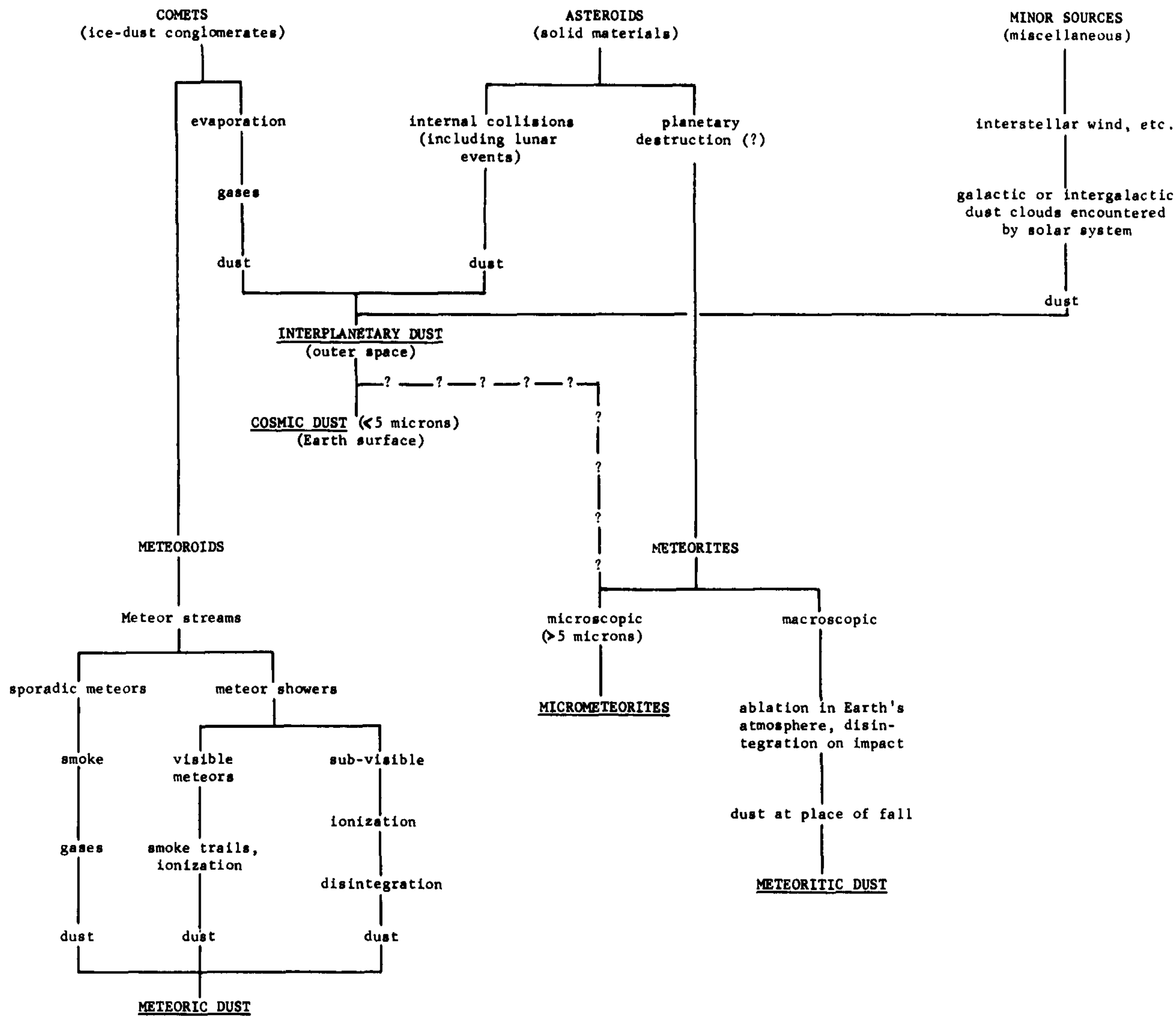


Figure 4. Average cumulative-mass distribution of interplanetary dust near the earth (after Alexander et al., 1962).

TABLE I: 8

SOURCES OF MICROSCOPIC EXTRATERRESTRIAL PARTICLES
(after Robey, 1959)



Appendix II

LOCATIONS OF MICROSCOPIC EXTRATERRESTRIAL PARTICLE OCCURRENCE ON THE EARTH'S SURFACE

(expanded from Buddhue, (1950) and Hodge et al (1961))

Investigator	Date	Location	Remarks
Mayer & Van Stoop	1819	Flanders	"red rain"
Pictet	6-21-1821	Majo, Spain	iron particles in hail-stones
Eversmann	6-11-1825	Sterlitamak, Siberia	iron & sulfur in hailstone
Cozari	8-26-1834	Padua, Italy	iron particles in hail-stones
Ehrenberg	2- 7-1839	Baku, USSR	"black, polished hollow kernels"
von Reichenbach	1859	10°38'S Lat.; 117°49'E Long.	shower of "bird-shot"-like black particleson ship
Ehrenberg	1-25-1859	Indian Ocean	fine metallic dust
Nordenskiold	7-19-1870	Greenland	fine metallic dust in snow
Nordenskiold	12, 1871	Stockholm, Sweden	black metallic particles in snow
Nordenskiold	3-13-1872	Evoia, Finland	soot-like metallic iron particles in snow
Arctic Exped. 1872	8- 8-1872	80°N Lat.; 13°E Long.	small, black metallic iron particles on snow
" " "	9- 2-1872	80°N Lat.; 15°E Long.	0.1 - 1.0 mglm^3 black metallic iron particles in snow (0.25 mm diam.)
Nordenskiold	fall 1873	Stockholm	metallic iron in hail
Tissandier	1873	St. Marie du Mont, France	124 mg of magnetic material from rain

Appendix II con't.

Investigator	Date	Location		Remarks
		Latitude	Longitude	
Murray	1876	42°42'S	134°10'E	magnetic spherules
		11°24'N	143°16'E	225, bronzite spherules
		35°41'N	157°42'E	241 ?
		35°22'N	169°53'E	244, cosmic spherules
		37°52'N	160°17'W	252, " "
		12°42'N	152° 1'W	265 magnetic spherules
		7°25'S	152°15'W	274 " "
		13°28'S	149°30'W	276 " "
		32°36'S	137°43'W	285 cosmic spherules
		33°29'S	133°22'W	286 magnetic spherules
		36°32'S	132°52'W	287 " "
		36°48'S	42°45'W	327 " "
		21°15'S	14° 2'W	338 magnetic & bronze spherules
		2°42'S	14°41'W	346 " " " "
		0°15'S	14°25'W	347 " " " "
<u>Vega</u> Exp.	8-13-1878	Taimyr Pen., Siberia		oldhamite (?) xls in snow
Silvestri	3-29-1880	Catania, Sicily		yellow dust containing steel gray metallic spherules + Ni
Lasaulx	1880	Kiel, Germany		metallic iron particles in snow
Nordenskiold	1883	San Fernando, Chile		red-brn spherules in snow, + Ni
Jung	1883	Montreux (L. Geneva) Switzerland		iron particles in snow
		St. Bernard, Switz.		" " " "

Appendix II con't.

Investigator	Date	Location	Remarks
Batchelder	1885	Pelham, N.H. USA	iron dust from rain
Kammerman	11-27-1885	Gent, Belgium	'meteoritic particles'
Hartley & Ramage	11-16-1897	London, England (?)	magnetic spherules
Palmieri	3-10-1901	Africa	magnetic particles
Meunier	5-27-1903	64°54'N Lat. 13°40'E Long.	black spherules, glassy globules
?	1924	Washington, D.C. USA	transparent glassy spheres + mineral grains
Radaux	1927-1933	Donville, Mandie, France	magnetic particles from rain, air
"	9-1927	"	particles associated w/ fall of fireball
"	10-9-1933	"	particles associated w/ Draconid meteor shown
"	1927-1933	Pyrenees Mts.	magnetic particles from snow
Makemson	1931-1932	Winter Park, Fla. USA	clear, fragile globular particles
Spencer	1933	Henbury, Aus. & Wabar, Arabia	meteoric iron and glass
Schloss	1935	Lake Obalski (300 kms)	magnetic particles
?	1939	James Bay, Canada	magnetic particles & qtz, feld.
Nininger	1940	SW USA	magnetic particles from rainwater + Ni
Revelle	1944	29°21'N Lat. 132°20'W Long.	1 magnetic spherule
Landsberg	11-16-1946	Mt. Westner, Va., USA	black magnetic spherules from rain. w/ Draconid meteor shower? 0.022 mm
Norris and Hogg	Summer 1948	Heliburton, NWT Canada	magnetic spherules from air. + Ni
	Winter 1948	Ft. Smith, " "	

Appendix II con't.

Investigator	Date	Location	Remarks
Divari	1948	Tian-Shan, China	snow-no cosmic dust
Malyuga	1948	Alma Ata., USSR	dust in snow (probably terrestrial)
Phipson	9-1948	?	black, angular particles w/ Perseid meteors?
Buddhue	1950	Pasadena, Calif.	meteoritic dust
Krinov & Fonton	1952	Russia	metallic spherules
Pettersson	1952	Central Pacific (?)	Ni, Fe, Mn in sediments
Thomsen	1953	Iowa City, Iowa, USA	magnetic spherules (no Ni)
	1953	Iowa City, Iowa, USA	Thomsen's stuff is terrestrial
Ahnert	1954	Germany?	magnetic and nonmagnetic spherules
Kizilirmak	1954	Ankara, Turkey	irregular magnetic dust
Heard	1955	Arctic?	magnetic spherules
Opik	1955	ocean (from Pattersson)	Ni-dust
Laevastu & Mellis	1955	7°38'S Lat. 152°53'W Long.	black spherules
Smales, *et al*	1955	ocean sediments	magnetic spherules
Bruun, Langer & Pauly	1955	3°54'N Lat. 8°22'W Long.	
		0°42'N Lat. 5°59'W Long.	1°00'S Lat. 76°17'E Long.
		2°17'S Lat. 8°10'E Long.	12°47'N Lat. 116°24'E Long.
		35°00'S Lat. 27°22'E Long.	35°00'S Lat. 39°45'S Long.
		35°12'S Lat. 27°35'E Long.	45°47'S 164°39'E Long.
		34°56'S Lat. 36°31'E Long.	
		8°52'S Lat. 49°25'E Long.	
		7°24'S Lat. 48°24'E Long.	
Crozier	1956	N. Mexico, USA	black magnetic spherules
Fredriksson	1956	Pacific Ocean	black spherules
Hasegawa	1956	Japan	black spherules, silicate spherules

Appendix II con't.

Investigator	Date	Location	Remarks
Stoiber *et al*	1956	Arctic Ice Island T-3	magnetic spherules
Suslu	1956	Ankara, Turkey	metallic spherules
Rinehart	1957	Meteor Crater, Am USA	metallic spherules
Yavnel	1957	Tunguska Meteorite USSR	black, shiny globules
Astapovich	1958	USSR	meteoric spherules and dust
Hodge & Wildt	1958	48°00'N Lat. 122°22'W Long. 46°50'N Lat. 121°45'W Long. 34°30'N Lat. 117°30'W Long. 65°N Lat. 148°W Long. 75°N Lat. 95°W Long.	opaque shiny spherules
Kolomensky & Yudin	1958	USSR	crust of Sikhote-Alin meteorite
Pettersson & Fredriksson	1958	7°38'S Lat. 152°53'W Long. 3°21'S Lat. 174°12'E Long. 3°21'S Lat. 174°12'E Long. 1°20'S Lat. 167°23'E Long. 11°33'S Lat. 91°26'E Long. 33°59'N Lat. 31°02'E Long. 43°28'N Lat. 7°22'E Long. 41°29'N Lat. 5°51'E Long. 2°23'N Lat. 173°50'W Long. 2°48'S Lat. 178°57'W Long.	magnetic spherules
Smales *et al*	1958	Pettersson's samples	Ni bearing magnetic spherules
Kreiken	1959	Ankara, Turkey	iron particles & meteoritic origin
Nishibori and Ishizaki	1959	69°00'S Lat. 39°35'E Long.	black spherules
Hunter and Parkin	1959	34°11'N Lat. 52°32'W Long. 24°30'N Lat. 64°47'W Long. 27°07'S Lat. 115°10'W Long.	spherules
Yagoda	1959	Crosby, Minn. Holloman AFB, N. Mex.	Ni-bearing dust

Appendix II con't.

Investigator	Date	Location	Remarks
Crozier	1960	Carthage, N. Mex.	black, magnetic spherules
		Glendale, Canada	
		Big Bend, Texas	
		42°43'N. Lat. 142°13'W Long.	
		44°31'S Lat. 127°14'W Long.	
		Lake Chicago, Wisconsin	
Krinov	1960	USSR	metallic spherules
Pettersson	1960	Hawaii	metallic spherules
		Mediterranean	
		Central Pacific	
Crozier	1961	Socorro, N. Mex. USA	magnetic spherules
Fredriksson	1961	Hawaii	metallic spherules
Hunter and Parkin	1961	Barbados	metallic spherules
Skolnick	1961	S. California, USA	magnetic spherules
Thiel and Schmidt	1961	90°S	metallic spherules in Antarctic
		80°S Lat. 120°W Long.	ice
		80°26'S Lat. 169°35'E Long.	black spherules
Crozier	1962	Magdalena & Mt.	black spherules
		Withington, New Mexico	black spherules
Langway	1962	Greenland	black spherules
Parkin, Hunter and Brownlow	1962	England	coated spherules
Wright and Hodge	1962	U.S.	black spheres from air
Schmidt	1963	74°14'S Lat; 84°46'W Long.	micrometeorites from snow
		74°03'S 80°32'W	
		74°56'S 76°01'W	
		74°52'S 71°28'W	
		74°50'S 71°43'W	
		74°16'S 70°10'W	
		73°33'S 68°38'W	
		74°04'S 66°35'W	
		74°58'S 68°12'W	
		75°27'S 72°21'W	
		75°22'S 74°56'W	

APPENDIX III

CHRONOLOGICAL RESUMÉ OF PREVIOUS WORK ON MICROSCOPIC EXTRATERRESTRIAL PARTICLES (SINCE 1945)

A brief chronological resumé of previous work on microscopic extraterrestrial particles since 1945 is presented below. The date 1945 was chosen as a limit for the present historical review of studies on such particles because Buddhue's (1950) monograph contains a survey of nearly all such research before that time. To allow this presentation to be employed as an extension of Buddhue's review to the present day, the form which he established will be observed.

1945 V'iunov discussed the role of meteor streams in the causation of magnetic storms and polar aurorae. It was concluded that cosmic dust may cause disturbances of the terrestrial magnetic field. The greatest magnetic storm and auroral activity was found in March and in September-October, coinciding with the periods of meteor showers.

1947 Landsberg reported collections of atmospheric dust collections at Mt. Weather and Arlington, Virginia. Twenty-five opaque, magnetic particles were described. These ranged in size from 0.005 mm to 0.1 mm diameter. The magnetic particles were thought to be related to the Giacobinid meteor shower, as no magnetic particles were recovered in the week before that event.

1949 Fesenkov discussed the brightness of the zodiacal band and the total mass of asteroidal matter. The total mass of asteroidal material that produces the phenomenon of the zodiacal light is proportional to the minimum size of particles. It was concluded that the transition between the asteroids and small fragments of matter is not continuous. Fairly large bodies, measured in kilometers, add nothing to the brightness of the zodiacal belt. Rather, it is produced by smaller, secondary material which originated as a result of continuous fragmentation in the region of the asteroidal ring.

Norris and Hogg reported collections of magnetic meteoric dust from the air. Contamination from local sources was found, but many particles gave positive tests for nickel and were considered of meteoritic origin.

Whipple defined the term micrometeorite as an extraterrestrial body that is sufficiently small to enter the earth's atmosphere without being damaged by encounter with the atmosphere. The limiting circumstance arises when the micrometeorite radiates energy rapidly enough that its temperature remains below its melting point as its motion is retarded by the atmosphere. The limiting radius for a spherical micrometeorite varies approximately as the fourth power of the melting temperature, the inverse cube of the velocity, the inverse logarithmic density gradient at the point of maximum temperature, and the secant of zenith distance; it is about 3 to 5 microns. Larger particles (20-40 microns) may have been partially vaporized.

1950 In this year Buddhue published a monograph on "meteoritic dust." This valuable work contains a chronological survey of studies of such particles. Buddhue collected cosmic dust from the air in cans and on sticky slides, and to a lesser extent, from rain and snow. His work produced a valuable classification of such material, which is presented in an earlier section of this survey. The bulk of particles collected had physical properties and chemical compositions most closely akin to those of magnetite than to other known minerals. On the basis of measurements of grams of dust per centimeter of rainfall, the annual deposit of cosmic dust was estimated to be from 8 metric tons per year to 126,000 metric tons per year over the entire earth. The particles examined were thought to have been formed by ablation of meteorites during their passage through the earth's atmosphere.

Link suggested that there is a layer of meteoritic dust in the earth's atmosphere in order to explain light absorption observed during lunar eclipses.

Pettersson and Rotchi described analyses of sediment cores from the Pacific Ocean, in which unusually high amounts of Ni were found. The NiO content of the samples was roughly in inverse proportion to the rate of sedimentation. The origin of nickel in the sediments could have been from (1) sea water, (2) submarine vulcanism, or (3) cosmic dust. A cosmic origin was favored.

Whipple proposed his "icy comet" hypothesis, in which the cometary nucleus is thought to consist of a conglomerate of ices in which solid dust particles are embedded. Vaporization of the ices by externally applied solar radiation frees the dust particles, which are then distributed along the comet's path through space.

Wyatt and Whipple discussed the Poynting - Robertson effect on small particles occurring in the solar system. They noted that the Poynting - Robertson effect will operate to sweep small particles of the solar system into the sun at a cosmically rapid rate. Because of this, they viewed meteor showers as originating from comets.

1951 Blanco reported collections of micrometeorites from rainwater and balloons in Puerto Rico. Several magnetic particles were obtained.

Ovenden reviewed the meteor hazards to space travel. Heavily armored hulls or "meteor bumpers" were recommended for long-lived space stations.

Struve discussed in general the nature and occurrence of dust in our solar system.

Whipple discussed the theory of micrometeorites - small particles which can radiate energy fast enough that they do not suffer melting by atmospheric friction - in heterothermal atmospheres. A rigorous mathematical treatment of the problem was presented.

1952 Beals discussed the materials of interstellar space, thought to be parts of the process of star formation. Gases and dust particles and clouds were viewed as especially important for this process.

Gold showed that the dynamical interaction between galactic gas and those dust particles which are elongated will lead to a partial alignment of the particles under certain circumstances. The direction of alignment is that of the relative velocity between gas and dust.

Hoffleit compiled an annoted bibliography on meteoritic dust. A total of 505 references were listed.

Krinov and Fonton detected cosmic dust at the place of the fall of the Sikhote-Alin iron meteorite shower in the Soviet Union. They found traces of melted matter on the surfaces of these meteorites, and postulated that the dust particles were swept from the melting surfaces of meteoric bodies during passage through the earth's atmosphere.

Millman surveyed data on meteor astronomy. The daily accretion of meteoritic material by the earth was estimated to range from 10^3 to 10^4 tons.

Nininger discussed micrometeorites in a general description of meteorites and their occurrence in North America.

In this year Pettersson reported that the nickel content in most sediment cores from the central Pacific ocean was much higher than the average value for normal continental rocks and sediments. It was suggested that this high nickel content may be caused by the presence of cosmic dust particles in the sediments.

Dalton suggested that meteoritic material encountered by the earth may represent fragments resulting from destruction of a planet between the orbits of Mars and Jupiter. This was offered in exploration of the object responsible for Meteor Crater, Arizona.

Thomsen collected magnetic spherules in Iowa City, Iowa on March 14, 1951 following a heavy snowfall. Gravimetric analysis showed Fe_2O_3, 72%, SiO_2, 28%, with the presence of Ni doubtful. The magnetic spherules ranged from 0.008 mm to 0.08 mm in diameter. The annual deposit of such material over the entire earth was calculated as 2,000,000 metric tons per year, with the adopted density of particles as 4.

1953 In the same year Handy and Davidson noted that industrial fly-ash produced in quantity in the midwestern United States, has essentially the same composition as the 'meteoritic dust' particles reported by Thomsen. They noted that "from a spectroscopic analysis Thomsen reported nickel as 'doubtful' in his samples; the authors believe that the identical adjective applies to the meteoritic origin of at least a part of his samples (for this reason)."

1954 Ahnert also doubted whether Thomsen's metallic spherules are of meteoritic origin. He noted that similar nickel-free dust was collected near factories.

Herzberg described studies of the spectra of interstellar material. Diffuse interstellar spectral lines were not considered as due to absorption by atoms of the Fe group embedded in interstellar grains. Rather, they were attributed to transitions of negative atomic ions (O^-, C^-, N^-, etc) from their ground states to preionized states, corresponding to excitation of an inner electron.

Kaiser and Seaton discussed the relation of interplanetary dust to the physical processes in the upper atmosphere of the earth. It was concluded that the density of such particles is too low to play any significant role.

In this year Kizilirmak recovered metallic spherules from snow in and around Ankara, Turkey. The spherules contained iron, but no nickel, cobalt, or magnesium. More particles appear to have been recovered in the summer months; he noted a steady increase of particles until a maximum was reached at the beginning of July, afterwards a slow decrease occurred in the number of particles collected.

Svestka examined Link's (1954) proposal that there is a layer of meteoritic dust in the atmosphere and concluded that particles larger than one micron cannot produce the absorption observed, and meteoritic dust was probably formed from smaller particles on the order of 10^{-5} to 10^{-6} cm.

1955 Bowen examined rainfall figures for many sites, and discovered that there is a tendency for more rain to fall on certain dates than on others. A close correspondence between the dates of rainfall maxima were found for both northern and southern hemispheres. The rainfall peaks occurred approximately 30 days after prominent meteor showers, and it was suggested that they were due to the nucleating effect of meteoritic dust falling into cloud systems in the lower atmosphere, the time difference being accounted for by the rate of fall through the atmosphere.

Bruun, Langer, and Pauly collected magnetic spherules from the deep ocean bottom with a magnetic rake. Several types of particles were recovered, some of which contained iron and nickel. Other particles had a silicate groundmass "loaded with magnetic crystallites." It was proposed that atmospheric ablation of stony meteorites may be responsible for the formation of such particles. Ablation of iron meteorites was viewed as a likely cause of formation of the metallic spherules. Quenching experiments with iron-nickel-carbon melts showed that spherules very similar in every detail to ocean-bottom particles can be artificially produced by rapid cooling of liquid metal. This evidence appears to support the hypothesis that these particles were formed by meteoritic ablation. The annual deposit was estimated to be about 30 metric tons.

1955 Buddhue reported a collection of meteoritic dust from the Geminid shower of 1949. A total of 477 meteoritic spherules were collected on one slide; of these, 326 were black, 139 were siliceous, and 12 were metallic.

deJager stated that "the observed deposit of extraterrestrial dust on the earth is by a factor of about 1000 greater than the deposit computed on the basis of observed meteor frequencies." Dust particles were thought to be captured in satellite orbits around the earth, and drawn closer to its surface by the influence of solar radiation (Poynting - Robertson effect). It takes only a short time for the particles to fall to earth, from the continuous supply furnished by this effect. The daily deposit of dust was extimated to be between 1.6 billion grams and 9 billion grams.

Heard reported that more spherules were recovered from air sampling over industrial centers (Windsor, Ontario, Canada) than in the Arctic. "No bright metallic spherules were found, and the particles that were are probably not meteoritic."

Kallmann has compared meteoritic dust with interplanetary (zodiacal) dust in the size range 0.5 mm to 0.002 mm. It was found that there were two categories of dust particles in space; dense, fast moving meteoric particles "in all probability of cometary origin," and less dense, slower-moving quiescent dust particles which are more abundant than the meteorids and "whose origin might be connected with the origin of the planets."

Laevastu and Mellis studied material described by Pettersson (1952). They adopted a density of 5.2 for the spherules, and estimated that about 125 tons per year of black cosmic spherules ranging in diameter from 0.01 mm to 0.23 mm reach the earth. It was noted that the high nickel content of sediment cores reported by Pettersson is too great to be accounted for by the cosmic spherules. Instead, it was suggested that the iron and nickel appear to be derived in part from coprecipitation from sea water.

Lebedinsky stated that "stars are originating as a result of gravitational condensation of diffuse matter (presumably dust). Diffuse matter is used up in formation of stars, but this is compensated by the ejection of matter from stars, creating a steady state system."

Levin found that the spatial density of dust particles decreased by a factor of 1/R with increased distance from the sun. (The same relation was reported by others around this time also). In the vicinity of earth, the density of particles was calculated to be about 10-23 g/cc.

Minneart noted that information on interplanetary dust may be obtained from (1) the zodiacal light, (2) the solar corona, and (3) meteors. He notes that methods (1) and (2) provide more information on the particles than can be inferred from meteors. Dust particles were found to occur in the ecliptic plane, increasing in concentration as the sun is approached. The total mass of interplanetary dust was estimated at

10^{18}g. The interplanetary dust was thought to originate from meteoroid bombardment or from comets in such a way as to replenish the dust lost to the sun by the Poynting - Robertson effect.

1955 Oört noted that interplanetary dust is absent in elliptical galactic systems and certain nebulae, but is quite common in spiral nebulae. He attributed an important function to the interplanetary gas in which the dust particles occur, viz, they are produced by condensation of the gas, and represent condensation nuclei.

Öpik suggested that the unusually high nickel content of deep-sea deposits of the Pacific Ocean were due to concentrations of nickel-bearing cosmic dust, along the same lines as Pettersson (1952). This was proposed following examination of some of Pettersson's samples.

Öpik noted that data on observational meteors indicated that they were a spongy, dust-ball type of much lower average density than that of the minerals of which they consist. They seemed to "decompose" (pulverize) from aerodynamic pressure, along the lines of Whipple's comet model.

In another paper of this year, Öpik found that (the major fraction of space-density, and from 30% to 40% of the recorded meteor numbers belong to the class of zodiacal particles). The distribution of heliocentric motions of this material was concentrated in the plane of the ecliptic.

Stromgen noted that interplanetary dust particles contributed only about 1 to 2% of the total mass in space. The heavy element content of interstellar matter was about equally divided between the gaseous component and the dust particles; its total abundance was about 3%. The diffusion of interstellar dust particles through the interstellar gas under the influence or radiation pressure was slow, and the distribution of interstellar gas and dust was "generally identical." Dust and gas clouds were present in "dark nebulae." Large agglomerations of interstellar matter have been viewed as the place of star formation, but evidence from chemical compositions was "definitely against any mechanism of star formation that is characterized by concentration of the dust component relative to the gas component of interstellar matter."

van de Hulst reviewed the status of data on the likely properties of interplanetary dust particles. He estimated that the particles were at low temperature (10 to 40 degrees K); probably composed of ices of water, ammonia, methane, and metal impurities less than 1 micron in diameter, i.e. smaller than expected (some process is thought to limit their rate of growth); shaped like needles of flakes; and concentrated on the order of 10-13 particles per cc near the ecliptic plane. The dust particles were thought to act on the interplanetary (solar?) gas, cooling it and also absorbing radiation.

Whipple discussed the amount of material added to the solar system by comets. "Some 30 tons/second of meteoritic material are contributed continuously in typical comet orbits..." However, most of this (all

but about 3.5 tons/second) is lost by the effects of interstellar wind, collision, and Poynting - Robertson effect.

1956 Berg and Meredith discussed results of a high-altitude rocket experiment in which an impact detector, was flown to measure micrometeorite flux. Almost all recorded impacts occurred at altitudes greater than 85 km, and it was suggested that they were caused by meteoroids.

Bracewell measured the freezing nucleus concentration at Palo Alto, California daily during the month of January, 1956. Maxima were discovered on dates corresponding to meteor showers.

Burgess reviewed apparatus used in high altitude experiments, and described measurements of micrometeorites conducted by means of microphone detectors. No altitude dependence was shown by the impacts recorded, and it is possible that terrestrial dusts were encountered.

Crozier collected magnetic spherules from the air in New Mexico. He found that the rate of deposit of these particles might be correlated with meteor showers.

Dubin described an experiment for the detection of meteoric particles by means of an artificial satellite. A brief review of the subject, together with description of an acoustical particle detector for satellites, was presented.

Fredriksson found "several hundred black spherules, greater than 35 microns diameter, from different layers in the cores" taken by the Swedish Deep-Sea Expedition. These particles were composed of metallic iron nuclei surrounded by magnetite. The spherules were thought to be of Tertiary age, and the depth of their occurrence precludes any industrial contamination. They were thought to be of 'cosmic' origin.

Griffith, Nordberg, and Stroud reviewed available data on the environment of an earth satellite. One section of this review dealt with meteorites and micrometeorites.

Mayne examined the problem of the origin of helium in the earth's atmosphere. As a result of this work, it was proposed that helium may be produced in extraterrestrial dust by cosmic radiation, and that dust particles contribute helium to the atmosphere as they encounter the earth. It was estimated that about 5000 tons of dust particles are deposited over the earth's surface each day.

Plavec discussed the evolution of meteor showers. He noted that "although a relationship of several showers to the minor planets (asteroids) cannot be excluded, the majority of the streams no doubt are of cometary origin." Ejections from comets by internal forces appeared to be the main causes of meteor streams.

Singer reviewed knowledge about interplanetary dust particles, and presented a preliminary account of a simple charged-dust theory. These considerations were then applied to possible satellite experiments.

1956 Stoiber, Lyons, Elberty, and McCrehan found magnetic (magnetite) spherules ranging in size from 0.005 mm to 0.1 mm in deep cores on Arctic ice island T-3. They were thought to be 'probably extraterrestrial.'

Süslü collected iron dust from the air at Ankara, Turkey. He noted that "it is probable that the iron particles are related to meteorites which are visually observed," although they did not contain any nickel.

Hecht and Patzak reported chemical analyses of cosmic spherules recovered by the Swedish Deep-Sea Expedition. Compositional similarity with meteorites was found for Fe, Ni, and Co. A meteoritic origin was proposed.

1957 Dufay postulated that "dust particles (are) formed by condensation of intergalactic gas."

Hoenig reviewed the hazards of meteoroids for space flight. For short periods of time hazards were regarded negligible.

Ludlam reviewed knowledge on noctilucent clouds. These are thin cirro-stratus like clouds visible about an hour after sunset. They occur between altitudes of about 78 to 89 km, and are illuminated by the sun's rays from beyond the horizon. The clouds occur mainly after mid-summer, are restricted to between 55° and 70° North latitudes. Particles in the clouds were estimated to be less than one micron in diameter, with concentrations of 10^{-16} g/cc. Noctilucent clouds may be composed of ice particles, volcanic dust, meteoritic dust, or interplanetary dust. The clouds are most likely composed of small solid particles, which may originate from terrestrial volcanic eruptions or from meteors.

Stephenson reviewed the nature of interstellar dust, and especially the problem of whether it could be accreted through interaction with interstellar gas. It was concluded that such interaction cannot compensate for the influence of radiation pressure.

Yavnel reported nickel-iron particles 0.03 mm to 0.06 mm in diameter ocurring in soil samples at the place of the fall of the Tunguska meteorite in the Soviet Union. He concluded that these particles were part of the meteorite.

1958 Astapovich concluded from a study of work on meteoritic dust and cosmic dust in the earth's atmosphere that more than 16,000 tons fell on the earth each year.

Castaing and Fredriksson analyzed cosmic spherules from the Pacific Ocean with the x-ray microanalyzer. They found nickel to be present, and in greatest abundance (up to 31.6%) in the metallic nuclei of iron-nickel spherules. They considered it "most probable" that the spherules formed as drops drawn off bigger meteorites by friction against the atmosphere.

1958 Hodge and Rinehart collected dust from high altitudes using high-flying jet aircraft. "Some dark, shiny metallic particles may be extra-terrestrial, since their abundance does not change rapidly with altitude, as with particles of terrestrial origin."

Hodge and Wildt collected opaque, shiny spherules less than 0.015 mm diameter on sticky slides. They were thought to be of meteoritic origin, in that the rate of fall and frequency distribution of particle sizes was found to be the same at several widely separated stations. Assuming that the density of the counted particles was that of magnetite, the annual accretion for the entire earth was estimated to be 500,000 metric tons.

Kolomensky and Yudin discovered spherical particles in the fusion crust of the Sikhote-Alin meteorite. This appeared to support an origin of such material by ablation of iron meteorites during passage through the earth's atmosphere.

Pettersson and Fredriksson described a study of cosmic spherules in sediment cores from the Pacific Ocean. The number of spherules was determined in various sediment fractions of several drill cores, but no correlation of spherule maxima between cores was possible. Spherules were found to occur in Tertiary sediments, refuting the hypothesis that meteoritic falls were limited to the last 25,000 years. However, there were strong indications that the frequency of spherules deposited in recent times was greater than in the past. (Or are the rocks just less perfectly compacted?) It was estimated that from 2,400 metric tons to 5,000 metric tons of spherules are deposited on the earth annually.

Smales, Mapper, and Wood analyzed some of the spherules collected by Pettersson, using radioactivation methods. They found that the spherules contained from 0.03 to 3.9 micrograms Ni, 0.01 to 0.3 micrograms Co, and 0.0006 to 0.53 micrograms Cu. They concluded that deep-sea spherules are closely similar to the iron meteorites.

1959 Barber and Sweitzer conducted a literature search of material on micrometeorites and related phenomena. A total of 282 articles were listed in an annotated bibliography.

Deirmendjian and Vestine described the nature of light from noctilucent clouds. The spectra may be explained in terms of primary scattering of direct sunlight by dielectric spheres with a maximum radius of 0.4 microns, and certain night sky emissions. The possibility of an ice composition of the clouds formed by condensation of terrestrial water vapor was found unjustified on physical grounds. Rather, a siliceous or similar composition and an interplanetary origin for the cloud particles was favored.

Dubin reviewed the nature of cosmic debris in interplanetary space, and described measurements of these particles conducted by satellites. The daily mass accretion rate of such particles to the earth, as determined by the Explorer I satellite, was 8.8×10^3 metric tons per day for all interplanetary materials.

1959 Fessenkov discussed the nature of the zodiacal light, and concluded that its properties can be accounted for by scattering of solar light by fine interplanetary dust particles. It was suggested that the dust particles originated from the periodic comets without any appreciable velocity at their disintegration.

Gazley, Kellogg, and Vestine reviewed available data on meteoroids in connection with a general discussion of the space environment.

Hasegawa presented a discussion on collecting meteoric dust, together with an examination of theories of origin. The most common collecting method used by Japanese workers was vaseline-coated slides exposed to the air. He summarized Japanese work on these particles. Most dust particles collected in Japan range from 5 to 50 microns in diameter. They contained iron and nickel, and it was estimated that 0.9×10^{-1} particles fell per cm^2 of the earth each day. The origin of particles was reviewed, and meteorite disintegration, meteor showers, and interplanetary dust was discussed as sources. The influence of meteorological variations on seasonal variations in dust occurrence was thought to be great. Most particles were thought to be due to meteorite disintegration.

Komissarov et al. discussed a micrometeorite detector used on Soviet rockets and satellites.

Kreiken summarized work on the fallout of meteoritic iron particles at Ankara, Turkey. It appeared that the number of particles was strongly affected by climatological conditions, and few particles were recovered following rainfall. A seasonal variation in the number of particles collected was noted: fewest particles were obtained in September, October, and November. It was estimated that 3,100,000 metric tons of iron particles fell on the earth annually. This appears to be the highest estimate of the annual deposit of meteoritic dust on record.

Krinov discussed nonterrestrial dust particles. Meteoric dust results from melting of a meteor in the earth's atmosphere; the particles are spherical and have an entirely different chemical and mineralogical composition from the bodies that produce them, due to oxidation of the particles in the air. Meteoritic dust is produced when meteorites strike the ground, and has the same composition as their parent bodies. Cosmic dust enters the atmosphere directly from interplanetary space, and is similar in composition to meteors. Micrometeorites are small particles with the basic properties of meteorites.

Lovering estimated that the influx rate of meteor particles during meteor showers may be as much as five orders of magnitude greater than the background rates given by satellite measurements.

Manring discussed results of micrometeorite measurements on 1958 alpha and gamma satellites. A maximum in flux rate of particles 10 microns in diameter or larger was obtained from 1 February to 7 May 1958. Unfortunately, the detector was apparently damaged by a meteor shower.

1959 Nishibori and Ishizaki described samples of micrometeorites recovered from snow at Syowa Base, Antarctica. The particle size ranged from 5 to 60 microns.

Parkin and Hunter reported collections of cosmic dust from the atmosphere. Black, magnetic spherules ranging from 5 to 35 microns were observed. One needle 240 microns by 20 microns was found. Coated metallic flakes were also obtained. Nickel was detected in these particles.

Redman discussed results of studies of the zodiacal light and solar corona, and their bearing on interplanetary dust. Particles influencing optical measurements were about 2 x 10^{-3} cm diameter, and had a space density of about 1 particle per cubic kilometer.

Robey presented a general discussion of meteoritic dust. Siliceous and magnetic spherules were thought to originate from vaporized meteorites at high altitudes in the earth's atmosphere. A large quantity of smaller-sized dust was believed to be cometary, either arriving directly from comets or indirectly from exploding or disintegrating meteoroids. The possibility that a portion of the influx of meteoroids may contain a sizeable percentage of frozen molecular fragments has influenced the results. A diagrammatic presentation of the sources of interplanetary debris was presented.

Whipple reviewed available data on solid particles in the solar system as a part of a symposium on space exploration. Suggestions for studies of these particles were offered.

Yagoda obtained dust particles on plastic surfaces during stratospheric balloon flights. Positive nickel tests were found for this material, and it "presumably formed by the disintegration of larger units entering the top of the atmosphere."

1960 Best reviewed the works of several investigators on the accretion of "meteoritic dust' by the earth. It was noted that by far the most numerous particles are of small size, 10 microns in diameter or less. Several possible sources of 'meteroitic dust' were discussed. These are (1) galactic dust outside the orbit of Jupiter which is attracted by the sun's gravitational pull; (2) asteroidal belt dust; (3) fragments of meteors; (4) cometary ablation; and (5) interstellar dust clouds encountered by our entire galaxy.

Briggs computed the space density of meteoric dust at many points in the solar system. The formula assumes the distribution of dust particles to have rotational symmetry about an axis through the sun which is normal to the ecliptic and also to have plane symmetry about the ecliptic. He concluded that there was a strong concentration of dust particles in the plane of the ecliptic with a sharp maximum at a distance of 0.06 a.u. from the sun.

1960 Brown estimated that about 480 meteorites per year strike the earth, from data on observed meteorite falls in selected areas. The space density of meteoritic bodies weighing one gram and more was calculated to be 10^{-12} particle per cubic kilometer.

Crozier recovered magnetic spherules from sediments ranging in age from Recent to Ordovician. It was estimated that about 150,000 metric tons of such spherules fall to earth each year.

Dmitriev, Mishina, Mikirov, and Cherenkova investigated the influence of cosmic dust on the intensity of radiation passed through the atmosphere. Weakening of solar radiation was observed during the period of major meteor showers.

Dokuchayev considered the electrical change produced during passage of meteors through the earth's atmosphere. The passage of a meteor through the upper layers of the earth's atmosphere is accompanied by the formation of a strongly ionized trail consisting largely of electrons and ions of the meteor material. It may be considered therefore, that the meteoric particle leaves behind it a cloud of well conducting gas, surrounded by a gas having a considerably lower conductivity. The luminous aureole surrounding a moving meteor was thus due to a corona discharge in the front part of the ionized trail.

Dubin compared the results of particle measurements by satellites 1958 Alpha and Pioneer I. A daily accretion rate for all types of interplanetary dust of 10^4 tons was indicated by these measurements. This is equivalent to 3,650,000 tons per year for the entire surface of the earth. Assuming that the particles move with a velocity of 30 km per second, the density of interplanetary matter at the position of the earth's orbit was 5×10^{-22} g/cc. There were indications, however, that the particles may move with a lower velocity relative to the earth. High impact values on one portion of the orbit of satellite 1958 Alpha were attributed to a meteor shower. Data from Pioneer I suggested that the particles are concentrated in the plane of the ecliptic. A daily variation in the number of particles impacting was noted, probably because of the heliocentric motion of the earth.

Feller-Kniepmeier and Uhlig described electron-probe microanalyzer analyses of metallic meteorites. Macroscopic meteorites were studied, not micrometeorites, but a valuable description of experimental procedure and sample preparation was included.

Fesenkov reviewed present knowledge on the occurrence, characteristics, and origin of both interplanetary dust and meteoritic dust. Primary emphasis was placed on Soviet work.

1960 Gallagher and Eshelman discussed radar measurements which suggested that the conventional view of a few streams of meteor particles plus a large background of independently travelling sporadic particles is no longer valid. Instead, most of the background activity is caused by particles concentrated into numerous shower orbits. The concentrations of particles are very small, and it was estimated that there must be millions of shower orbits which intersect the orbit of the earth. The number of independent shower orbits is so great, and the earth encounters a given grouping so rarely, that it would be practically impossible to predict the occurrence of particular showers. The observed particle groupings, as most meteoric material in the solar system was believed to be associated with past or present comets, may indicate the presence of a large number of very small, subvisible comets.

Hawkins discussed asteroidal fragments and large meteorites. If the influx of such objects has been constant, the earth has collected the equivalent of an asteroid 14 km in diameter during the last 5×10^9 yrs. It was estimated that the asteroids consist of 16.7% Ni-Fe, indicating a primary object that before breakup was intermediate in size between the moon and Mars. The space density of meteorites was shown to vary as $(\text{radius})^{-4}$ and the total mass of meteorites with radius between 1 cm and 1 km was at least 5.6×10^{-24}g cm^{-3}. The size distribution of particles produced by the crushing of rock was similar to that found for meteorites and suggests that meteorites undergo a considerable number of collisions in space.

Hodge conducted a study of meteoritic particles from the Arizona meteorite crater, and estimated that the total mass of the original meteoritic material which these particles represent was about 12,300 short tons. This work also included collection of atmospheric dust by high-flying vehicles. It was found that the amount of terrestrial dust at heights of 50,000 feet or more is greater than commonly believed. The influx of meteoritic particles into the earth's atmosphere was smaller than values generally quoted, only 28 particles per cubic meter of air, most in the size range from 3 microns to 6 microns in diameter.

Hunter and Parkin described studies of cosmic spherules collected from surface sediments of the Atlantic and Pacific Oceans. Three types of spherules were recognized: stones, stony-iron, and iron. The stones ranged in size from 15-500 microns, the stony-irons from 20-100 microns, and the irons from 20-384 microns. More spherules were found in the Pacific sample than in the Atlantic ones. The irons were blacker, smoother, and more rounded than the stones, which are quite gray and rough by comparison. Iron spherules contain up to 70% Ni in their center, but only about 1% in their oxidized shell. Stony spherules were less regular in form, often possessing craters on the surface. Creamy-white to pale yellow-green colorations were shown at the base of craters. The majority of stony spherules were solid gray-black throughout. The stones were a magnesium-rich, fine-grained olivine, and positive tests for nickel were obtained. The origin of the particles were probably from meteorites or from the zodiacal cloud.

1960 Jonah reviewed the physical properties of solid debris in space in connection with the design of space vehicles. The mass, density, and total number of particles were examined. If the density of meteors was taken as 0.3 gm/cm^3, a zero magnitude meteor of the dust ball type would be about 5 cm in diameter, and would contain about one million particles with an average density of about 4 gm/cm^3.

Krinov discussed microscopic dust particles from the Sikhote-Alin meteorite shower. He believes that meteorite showers are usually caused by fragmentation of one large meteorite as it passes through the atmosphere. In the process many microscopic dust particles become separated from the main meteorite mass. These have the fusion crust and morphology of meteorites, and differ from cosmic dust that enters the atmosphere directly from space in that cosmic dust particles are practically unaltered by impact with the atmosphere.

Krzeminski briefly described the matter occurring in space between the earth and sun. The article is a review of earlier work.

LaGow and Alexander studied direct measurements of particles by instruments on satellite 1958 Alpha and 1959 Eta. Assuming that a significant number of meteoritic particles were not in orbit around the earth, the daily influx of interplanetary matter on the earth (particles between mass 1.2×10^{-8} g and 1.2×10^{-10} g) is approximately 10^4 tons per day. A daily variation in the dust particle density near the earth was discovered.

Liller examined the tails of comets 1956h and 1957d photoelectrically. These studies showed that, at a solar distance of about two-thirds at an a.u., most of the radiation between λ 3400 and λ 6400 was of a continuous nature and redder than sunlight. This strongly suggested that spherules of iron in the comet tails, with an average diameter of 0.6 micron and mass of 8×10^{-13} gm, produced this radiation.

Maringer and Manning discussed metallographic examination of the heat-affected surface zone of the Grant meteorite. This zone serves as a record of the thermal gradient which caused it during aerodynamic heating as it fell to earth. The average rate of ablation was of the order of 1-2 mm per sec. If the meteorite spent 20 or 30 sec. in passing through the atmosphere, the estimated total amount of ablation would be of the order of 2 to 6 cm, less than predicted by earlier workers.

Nazarova reported the results of 'meteoritic dust' impacts on Soviet satellites and rockets. The density of meteoric matter in space near the earth was found to vary in time and with position. High counting rates on May 15, 1958 (four orders of magnitude greater than other values) suggested that the satellite encountered a meteor shower.

Neugebauer compiled an annotated bibliography of articles dealing with the space environment of the earth.

Pettersson presented a popular account of his 1958 work.

1960 Shaw reviewed data on solid particles in interplanetary space as a part of a larger work on the natural environment of space. He presented a comprehensive compilation of existing information and current thoughts on the asteroids, comets, meteors, and interplanetary dust. A valuable bibliography was included.

Squires and Beard noted that surface evaporation of comets takes place as these bodies approach the sun. The side facing the sun was warmed, and the material present there was lost from the comet, presumably forming its tail. Comets lost a considerable fraction of their mass during one flight, and their calculations suggested that an average comet nuclear radius could be as little as 300 meters if the material density is as much as 0.005 g/cc. The comet temperatures varied less than 25^{o} from an average value of 165^{o}k throughout their visible flight. Solar heating and evaporation were believed to be responsible for considerable changes in the cometary orbit. The material lost from the comet may have some sort of significance in connection with interplanetary dust.

1961 Alexander, McCracken, and LaGow reported exceptionally high interplanetary dust particle activity on satellite 1959 Eta at the time of the Leonid meteor shower. Many impacts of particles up to about 0.014 mm in diameter were recorded in a very short time.

Bain considered possible effects of magnetic field alignment on meteoric ionization. Field alignment of ionization along the earth's magnetic lines results in enhanced scattering efficiencies. The magnetic field can maintain such a field alignment on ionization produced by a meteor trail, perhaps explaining the long duration of some meteor trails. Both overdense and underdense meteors would have long duration facts from such an effect; however, underdense meteors would be detectable only on radar.

A considerable daylight radiant activity in the summer months was observed in Manchester, England, where these radiants lie very close to the plane of the ecliptic. This configuration placed the radiants within a few degrees of being parallel to the lines of force of the earth's magnetic field. Thus, any general concentration of sporadic meteors would manifest itself as an increase in activity in the summer months.

Beard noted that planetary and solar gravitational attractions, together with angular momentum considerations, would tend to concentrate interplanetary dust in the plane of the ecliptic. This concentration varies as the inverse three-halves power of the solar distance, according to Beard. Observations of the dust-scattered light in the solar corona showed that the concentration of dust in interplanetary space was 10^{-14} to 10^{-15} particles per cc at the position of the earth's orbit. However, space vehicle observations gave a flux density of 10^{-12} particles per cc at a height of 3000 km above the earth. These observations were taken to indicate the presence of a dust blanket about the planets.

1961 Bjork summarized current knowledge on the flux rate, mass, velocity, and density of meteoroids to assess their effects on space vehicles. The probability of meteoroid puncture as a function of vehicle area, exposure time, and skin thickness was examined and tabulated so that armor required to protect space vehicles could be determined.

Brown revised his earlier estimate of the total fall of meteorites upon the earth to 560 per year.

Cohen described measurements of the flux of small extraterrestrial particles using wire grids and microphones mounted on rockets and satellites. The mean influx of particles large enough to break the grid wires was likely to be less than 1.7×10^{-3} particles $/m^2/sec$, with short periods where the influx rates are greater than this value. The average influx of particles on microphone detectors was 5.7×10^{-3} particles $/m^2/sec$. The mass distribution of particulate influx was most similar to that found for large meteor(ite)s.

Crozier compared the annual mass accretion of particles to the earth as determined by satellites (390,000 metric tons) with that of ground level studies of magnetic spherules (90,000 metric tons). The satellite data were regarded as uncertain because of the possibility that many of the particles encountered may be in orbit around the earth.

Davison and Winslow described the hazards to space vehicles resulting from natural space debris. A brief review of the several types of materials which may be encountered in space was presented. A total of 78 references were listed.

Dingle argued that meteorite fall and dust influx is greater now than in the past.

Dubin described instrumentation installed on the Explorer I satellite to detect particulate matter in space. A diurnal dependence was shown by the fact that 90% of the impacts occurred on the dawn side of the earth between the hours of midnight and noon. Higher impacts registered over short times were ascribed to meteor showers. An estimate of 10^4 tons of interplanetary matter deposited on the earth each day was obtained.

Ericson, Ewing, Wollin and Heezen noted the presence of 'cosmic spherules' in abyssal sediments taken from the Atlantic Ocean.

Fesenkov reviewed investigations of meteorites and micrometeorites conducted by earlier workers.

Fireman and Kistner collected dust from altitudes greater than 40,000 feet using airplanes and balloons. The chemical composition of this material was very different from that of the deep-sea spherules. Fewer than 10% of the high altitude particles contained Fe, Ni, and Co in meteoritic proportions. The spatial density of opaque dust particles at high altitudes varied considerably, suggesting the existence of dust clouds. Their data indicated that about 30,000 metric tons of material with Fe/Ni ratios similar to that of meteorites fell to earth each year.

1961 Fisher discussed the erosion of iron meteorites in space. The maximum erosion rate was approximately 1.1 x 10^{-8} cm per year, suggesting that previous erosion estimates were at least an order of magnitude too large.

Fletcher reviewed Bowen's (1955) hypothesis that meteoritic dust particles serve as freezing nuclei for rainfall, citing arguments in favor of the hypothesis, as well as presenting criticisms of the theory. The principal objection to the postulated explanation was that no simple mechanism for limiting the size range of efficient nuclei or transporting agency has yet been discovered.

Fredriksson described work on spherules collected in Hawaii. While these were similar to cosmic spherules, their composition and structure are different. They were deficient in nickel and were usually thin, empty, fragile shells. These were thought to be of volcanic origin.

Fremlin suggested that the concentration of dust in the space near the earth was caused by ablation of meteorites which graze the outer portion of the earth's atmosphere.

Goettleman et al. reviewed data of meteor flux and mass obtained by terrestrial observations. They found that this information encompasses only the larger particles which may be encountered by a space vehicle. However, calculations from the zodiacal light scattering have produced estimates of the character and size of interplanetary dust particles. Four classes of material were postulated; (1) high density spheres about 20 microns in diameter, (2) low density particles less than 20 microns in diameter, (3) solid, high density particles about 1 micron diameter, (4) originalgalactic dust less than 1 micron diameter.

Satellite data showed that at some times meteoroid impacts were higher than at others. These were ascribed to many meteor shower orbits which intersect the orbit of the earth. Characteristic dimensions of these particle concentrations might be about 10^9 meters, since the intersection of a meteor stream with the earth might last from a few hours to a day. In addition, the measurements may indicate the presence of a number of very small, subvisual comets.

From this information, three theoretical models of meteoroid occurrence in space were examined. These were: (1) a continuous particle field, with no variation in the meteoroid flux with time; (2) meteoroid clouds in which the particle concentration varies with position in the cloud away from a center of highest particle density; and (3) an altitude-dependent version of the continuous particle field model in which a meteoroid halo or belt surrounds the earth to an altitude of about 4000 km.

Hagihara discussed gaps in the distribution of asteroids, and concluded that these result from the accumulated effects of disturbing actions by small masses passing close by.

1961 Hemenway, Fullam, and Phillips collected large quantities of very small, high density particles approximately 75 Å in size on high altitude aircraft flights over Antarctica. The composition of these particles were similar to meteorites. Because of their small size, they were named nanometeorites.

Hibbs concluded from particle impacts on sensors aboard satellite 1958 Alpha that the particles were travelling in closed orbits around the earth, without sufficient energy to escape from the earth's gravitational field. No apparent correlation between satellite position (relative to the earth's motion around the sun) and average particle impact rate was found. A decreasing impact rate with altitude was suggested by the data.

Hodge and Wright collected particulate matter from the upper atmosphere between 50,000 and 90,000 feet during aircraft flights. The average space density of particles larger than 3 microns in diameter was estimated to be 150 particles per cubic meter. The space density was found to vary considerably from place to place. Only a small percentage of these particles were thought to be possibly of extraterrestrial origin. An upper limit for the space density of dust was from 10 to 20 particles larger than 3 microns diameter per cubic meter, and an upper limit to the influx rate of meteoritic material was approximately one million tons per day. Two-thirds of all particles were between 3 and 6 microns in diameter.

Hodge, Wright, and Hoffleit compiled on annotated bibliography on interplanetary dust. 205 references, including many on particles here designated micrometeorites, were presented.

Hunter and Parkin found the remains of cosmic spherules in Tertiary rock from Barbados. The metallic nuclei of the spherules had been removed by weathering, leaving only the iron oxide outer shell. Density and x-ray data showed that this material is magnetite.

Ingham examined the nature and distribution of interplanetary dust by means of observations of light from high altitude experiments. The smallest sizes of particles in space were estimated to be 0.2 to 0.3 microns diameter. The mass density of particles in interplanetary space near the plane of the ecliptic was estimated to be about 10^{-24} gm cm^{-3}.

Isakovich and Roy discussed the acoustic method of detecting particles by earth satellites. They stressed that careful calibration of piezo-electric elements is essential to obtain usable data.

Jacchia and Whipple noted that meteors of interstellar origin would move in hyperbolic orbits around the sun. These were thought to be gravitational members of the solar system. The vast majority (more than 99%) "must be cometary in origin." The number of meteoroids produced by the encounter of meteorites with the moon was viewed as quite insignificant, and comets "seem to supply essentially all the visual meteors and probably also smaller meteoroids."

1961 Kaiser reviewed several methods for the study of interplanetary dust, among which are optical meteors, radio meteors, light scattering, accretion by the earth, rocket and satellite experiments, and atmospheric studies. A summary of results obtained by each method was presented.

Komissarov et al. described apparatus employed to measure the "solid component of interplanetary matter" on Soviet earth satellites. This consisted of a ballistic-sensitive plate, displacement of which by particle impact yielded an electronic signal proportional to the particle's energy. Particles with mass from 8×10^{-9} to 2.65×10^{-8} g were encountered with an average frequency of 10^{-4} impacts /m^2/sec. A sharp increase in the number of impacts was registered on May 5, 1958.

Laevastu and Mellis studied the size distribution of cosmic spherules found in sediments, and concluded that "the mass of particles in equal size (diameter) intervals remains constant, in accord with the relation

$$V_1 N_1 = V_2 N_2$$

where V = volume or mass of a single spherule in a given size group or diameter interval.
N = number of spherules in this size group.

LaGow, Schaefer, and Schaffert described equipment used on U. S. satellites to detect particulate matter occurring in space. An average flux of 3.6×10^{-2} impacts /m^2/sec was found. The mean daily number of meteoric particles striking the earth was estimated to be 4.0×10^{18} collisions/day.

Manring discussed the nature of interplanetary matter, and reviewed the progress made in study of these particles, including descriptions of space-borne micrometeoroid detectors. Suggestions for future studies of such materials were offered. These included techniques to determine particle mass, density, diameter, and composition from space vehicles.

McCracken and Alexander compared direct measurements of small interplanetary dust particles with new data from sensors on satellite 1960 Xi. The newer data agreed with previous work, and from this an average distribution curve for small interplanetary dust particles in the vicinity of earth was established. This showed "no discernible dependence on altitude of the spatial density of dust particles," and the postulated 'dust belt' around the earth was not supported by this work. The accretion rate of these particles on earth was estimated to be about 10,000 tons per day.

Rasool examined the effect of major meteoric showers on the densities of the upper atmosphere. With a daily accretion of 10^6 gm of interplanetary dust, 5% to 8% density increases at 344 km and 660 km altitudes will occur during major meteor showers.

1961 Rosinski and Snow calculated the size distribution of secondary particulate matter formed from condensing vapors in meteoric trains. The diameters of the particles were found to be approximately proportional to the size of the meteor. The particles were calculated to be smaller than 100μ in diameter. The average concentration of secondary particles was higher than that of sporadic meteors. Bowen's rainfall-hypothesis should be re-examined in light of these data.

Salisbury and Salisbury compiled an extensive annotated bibliography of lunar and planetary research.

Singer pointed out that rather than there being a 'dust belt' about the earth, there is in reality a "modest dust shell." He postulated a continuous increase in dust concentration to a maximum at about 2000 to 3000 km above sea level. This was only a few times the value of dust concentration in interplanetary space, not the factor of 1000 as given by Beard.

Skolnick examined magnetic spherules in well cuttings and cores of sedimentary rocks of Cretaceous, Miocene, and Pleistocene ages from central California. He postulated that this material was dominantly meteoritic in origin and that the earth had been subjected to the fall of meteorite showers since at least late Cretaceous time.

Soberman and Della Lucca studied particulate impacts upon detectors carried on satellite 1960 Zeta I. Most of the particles were found to be about 5 microns in diameter. Apparently, no particles larger than 10 microns were detected. The data suggested that there is a geocentric variation in the micrometeorite flux.

Soberman et al. described experiments with the "Venus Fly-Trap", micrometeorite collector rocket. In this work specially prepared particle collectors were exposed on an Aerobee rocket flight at altitudes between 88 km and 168 km above the earth, and were successfully recovered. Three types of particles believed to be of extraterrestrial origin were identified. These were (1) dense spheres, 16% of the total; (2) irregular submicron particles similar in appearance to meteorites, 72% of the total; and (3) extremely irregular ('fluffy') particles, 12% of the total. The particles ranged from 0.1 to 1.0 micron in diameter, with most having the smaller sizes. Electron diffraction studies were inconclusive, and the writers "... are beginning to suspect that micrometeorite particles do not have a crystal structure or that any original crystal structure has been scrambled by cosmic ray bombardment." The study indicates that (1) submicron particles are present in the region of space adjacent to the earth; (2) the particles had low impact velocities upon the detectors and may have been in orbit around the earth; and (3) an unexpectedly large number of particles were collected, suggesting the possibility of a meteorite shower.

1961 Thiel and Schmidt reported the occurrence of metallic spherules in Antarctic ice cores. From data on the particle size, number, and annual accumulation of snow at collecting sites, the annual deposit of spherules was estimated to be 184,000 metric tons.

Utech reported black, magnetic spherules from Tertiary sediments of Germany.

Whipple studied acoustical impacts of meteoritic dust on sensors carried on rockets and satellites, and this date "... show clearly that a high concentration of interplanetary dust occurs near the earth." The concentration of interplanetary dust was thought to decrease roughly as the inverse 1.4 power of the distance from the earth's surface, out to about 100,000 km, where it approximates the concentration of the zodiacal dust cloud. The dust in the vicinity of the earth was found to be between 100 and 1000 times more concentrated than in the zodiacal cloud.

In another paper, Whipple stated that the "small, particulate matter of the solar system can be viewed as originating primarily in comets, distributed originally from typical comet orbits, with a considerable concentration towards the plane of the ecliptic." He discussed the physical properties of the dust, and also meteoritic etching rates in space.

Wright, Hodge, and Fireman reviewed the status of studies of micrometeorites, and described collections of particles from the earth's atmosphere, using high altitude aircraft. The average space density of particles greater than 3 microns diameter was 250 particles per cubic meter at 50,000 feet altitude. This value increased greatly for lower altitudes and appeared to decrease slowly for higher altitudes. The bulk of particles were transparent or semi-transparent, with only about 1% resembling meteoritic material in appearance. These few particles led to an upper limit for the influx rate of meteoritic material of less than 10^6 tons per day.

1962 Alexander described cosmic dust experiments conducted by the Mariner II Venus probe. If the flux of dust particles in interplanetary space was assumed to be omnidirectional, about 10^4 times as many particles were encountered by satellites near the earth as were measured by Mariner II. Previous studies of dust particles in interplanetary space indicated a flux 10^2 times greater than the preliminary Mariner II value.

Alexander, McCracken, Secretan, and Berg reviewed rocket, satellite, and space-probe measurements of interplanetary dust. Measurements from microphone systems, photomultiplier and rocket collection systems, and fracture experiments were described and tabulated. These data were used to provide estimates of the cumulative-mass-distribution of the particles in the vicinity of the earth and the annual mass accretion rate (10^4 tons per day). The fluctuations of the influx rate, however, suggested that the dust particles are not in long-lived orbits around the earth. The average mass density of all particles was estimated at approximately 1 gm/cm^3.

1962 Carleton studied the experiments of Volz and Goody (1962), and concluded that interplanetary dust particles must be essentially in orbit about the earth. It was further concluded that their contribution to the total mass accretion was "not overwhelming", and any effects of ionization or excitation were negligible. The dust cloud about the earth was an adequate source of atmospheric dust, and about 260 metric tons per day are deposited on the earth.

Crozier described studies on black, magnetic spherules collected from the atmosphere in New Mexico over a five year period. The average numerical rate of deposition for spherules larger than 5 microns diameter was 2.8×10^{-3} particles/m^2/sec. The average rate of mass accretion to the earth was 1.6×10^5 metric tons/yr. The deposition rate dropped rapidly as diameters exceed 40 microns. Generally, maxima of spherule deposition were found in the spring and summer months.

Dole demonstrated that the thin cloud of dust particles concentrated in the space near the earth may be due entirely to the gravitational attraction of the earth. The velocities of most of the dust particles in space that are eventually captured by the earth were shown to be relatively low, permitting such concentration. Such particles, initially moving around the sun on direct orbits in the plane of the ecliptic can produce a steady-state dust cloud about the earth. The calculated particle flux was found to vary with the 1.66 power of the distance from the earth's center, agreeing with satellite observations. Individual dust particles were continually entering and leaving the dust cloud, but the concentrations remained constant over time.

Dubin and McCracken presented a summary of measurements of interplanetary dust. The cumulative distribution curve of the influx rate of dust particles as a function of particle mass may be described approximately by the equation

$$\log I = -17.0 - 1.70 \log m$$

where I is the influx rate in particles $m^{-2}\ sec^{-1}$ and m is the mass in grams in the range from 10^{-10} g $< M <$ 10^{-6} g. The spatial density of particles was estimated at 1×10^{-20}g cm^{-1}. The spatial density of dust particles near the earth was approximately 10^3 times greater than in interplanetary space. The accretion rate of interplanetary dust particles was about 5×10^4 tons per day.

Gallant argues that there is no reason not to suppose that meteorites fell on the earth before the "late Quaternary period," contrary to the views of Dingle (1961).

Harwit showed that radiation pressures in space can account for the formation of certain groups of stars, and for the acceleration of interstellar clouds in the vicinity of hot stars and galactic nuclei.

Magnolia compiled an extensive annotated bibliography on interplanetary matter of all types. A total of 1650 references were listed.

1962 Mason presented a general review of micrometeorites as a part of a discussion of the entire subject of meteorites.

Mirtov summarized Soviet Research on "solid interplanetary matter in its finely dispersed form (micrometeorites)." Collisions of satellites with particles of mass 10^{-7} g to 10^{-9} g were recorded, and estimates of 5000 to 10,000 tons per day were derived. A dust cloud is thought to exist around earth, increasing in density toward its surface. The maximum concentration of dust particles is estimated to be at a distance of 100-200 km from the earth's surface.

Newkirk and Eddy presented data obtained during high-altitude coronagraph observations.

Newkirk and Eddy investigated the influx of meteor particles in the upper atmosphere by stratospheric coronagraph observations. This study confirmed the existence of an aerosol layer at a height of approximately 65,000 feet, and most of these particles are probably terrestrial in origin. Above this layer, a sharp drop in particle concentration occurred, interpreted under the assumption that a steady state occurs.

Newkirk and Eddy, in another paper, gave a more general account of their high-altitude coronagraph experiments. An excellent description of the equipment used and techniques employed was presented.

Parkin, Hunter, and Brownlow described collections of atmospheric dust on the Isles of Scilly during 1961. The concentration of metallic iron varied, and showed three main peaks. These may be correlated with the Arietids, B-Taurids, and Perseids meteor showers if the dust is allowed a delay of about 3 weeks in falling from the upper atmosphere. This was in accord with Bowen's (1953) rainfall hypothesis. Iron-nickel and even pure nickel particles were observed. Attachments were sometimes found adhering to the metal particles. These were frothy-cream-color, with transparent nodular excrescences sprouting from the surface. In the dry state it gave no indication of the Ni metal flake embedded in it. Refractive index of the transparent, amorphous material was 1.547 to 1.540. This amorphous material might be partly organic, and where not charred by impinging on the atmosphere at high speed, may represent cosmic dust in its original state. A very nickel-rich flake of metal embedded in an amorphous material which had a refractive index of 1.549 was found in Antarctic melt water. In transmitted light it was a pale yellow-green, and in reflected light it appeared a frothy white or cream.

Parkin and Hunter reviewed the salient facts about meteorites in connection with a study of extraterrestrial dust particles. It was concluded that the dust particles were either meteoritic or meteoric in origin. Meteoritic particles were thought to originate from planetary destruction followed by subsequent internal collisions among the fragments. Meteoric particles were ascribed to ablation of cometary meteors, especially principal meteor showers.

The apparatus and techniques employed in collecting iron dust from the air were described, and the results of initial experiments were presented. It was found that the accretion rate of iron dust varies with meteoric activity, and that the particles fell to earth shortly after meteor showers. This does not support Bowen's rainfall hypothesis, which requires a larger time for particle settling.

Spherical particles were shown to be produced by melting of minute meteoritic fragments, (and thus should be classed as micrometeorites). Ablation of meteorites, once thought to be the cause of spherules, cannot produce sufficient material to account for the annual spherule deposit.

The iron flakes collected were thought to originate through the evaporation of volatile ices from cometary meteors, freeing the flakes to the meteor wake.

While in space, the particles would be electrically charged, which would inhibit any influence upon the path of the particles by the earth's magnetic field. This would be especially true if the particles were travelling at meteoric speeds. However, if ionized interplanetary gas exists, there would be strong interaction between the gas and the particles. The particles would be brought to rest with respect to the gas, and drift with it, perhaps becoming concentrated over the auroral zones of the earth. (This process would be aided if the particles travelled more slowly than meteoric velocities).

Riggs, Wright, and Hodge reported chemical analyses of particles collected by high-altitude aircraft and balloons. An electron-probe x-ray microanalyzer was used. Unfortunately, only a few particles are thought to be of meteoric origin; most are apparently of artificial origin.

Smith considered the problem of deposition in atmospheric diffusion of particulate matter. A mathematical development of the problem was presented.

Utech reported cosmic spherules from lower Triassic sediments. The main components of these particles were magnetite and olivine or bronzite. These are thus older than the late Quaternary, contrary to the work of Dingle (1961).

Valley reviewed data on space and planetary environments. Micrometeorites were only briefly mentioned, however, and will be the subject of a later survey.

Volz and Goody conducted measurements of the absolute intensity of twilight in an attempt to derive quantitative data on dust concentrations in the upper atmosphere. Maximum dust concentrations were found near 20 km elevation, fewer amounts at higher altitudes. A seasonal maximum of dust particles was observed during winter months.

1962 Wright and Hodge reported collections of extraterrestrial particles by high-flying aircraft. The mean space density of particles greater than 3 microns diameter were 4,000 per m^3 at 40,000 ft., and decreased to 1,000 per m^3 at 87,000 ft. The space density of small spherical particles (cosmic dust) was 3 per m^3 at 45,000 ft. The rate of fall of these particles was 0.3 spherule/an^2/day. About 2×10^8 kg of this kind of particle fell to the earth each year.

1963 Schmidt reported that greater amounts of larger black, magnetic spherules were deposited on Antarctica than in the southwestern United States.

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